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Effects of Conditioning Agents on Emissions from Coal-fired Boilers Test Report No. 1

Air Pollution Technology, Inc, San Diego, CA

Prepared for

Industrial Environmental Research Lab, Research Triangle Park, NC

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16. ABSTRACT

The report gives results of a field performance test of an electrostatic precipitator (ESP) which uses SO3 an the conditioning agent. The ESP is at an electric utility power plant, burning approximately 1% sulfur coal. Tests were conducted with and without injection of the SO3. The ESP performance was characterized in terms of particle collection efficiency and the chemical composition of particulate and gaseous emissions. Fly ash resistivity and dust opacity were also measured. Results show an average increase in overall efficiency from 80% to 95% with injection of the SO3. This is accompanied by a decrease in fly ash resistivity, a decrease in opacity, and an increase in SO3 concentration entering and leaving the ESP. Approximately 80% of the injected SO3 escaped the ESP.

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a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Electrostatic Precipitation	Pollution Control	13B	
Flue Gases	Fly Ash	Stationary Sources	21B	13H
Treatment	Electrical Resistivity	Conditioning Agents	14B	
Coal			21D	
Combustion	Opacity			20C
Sulfur Trioxide			07B	

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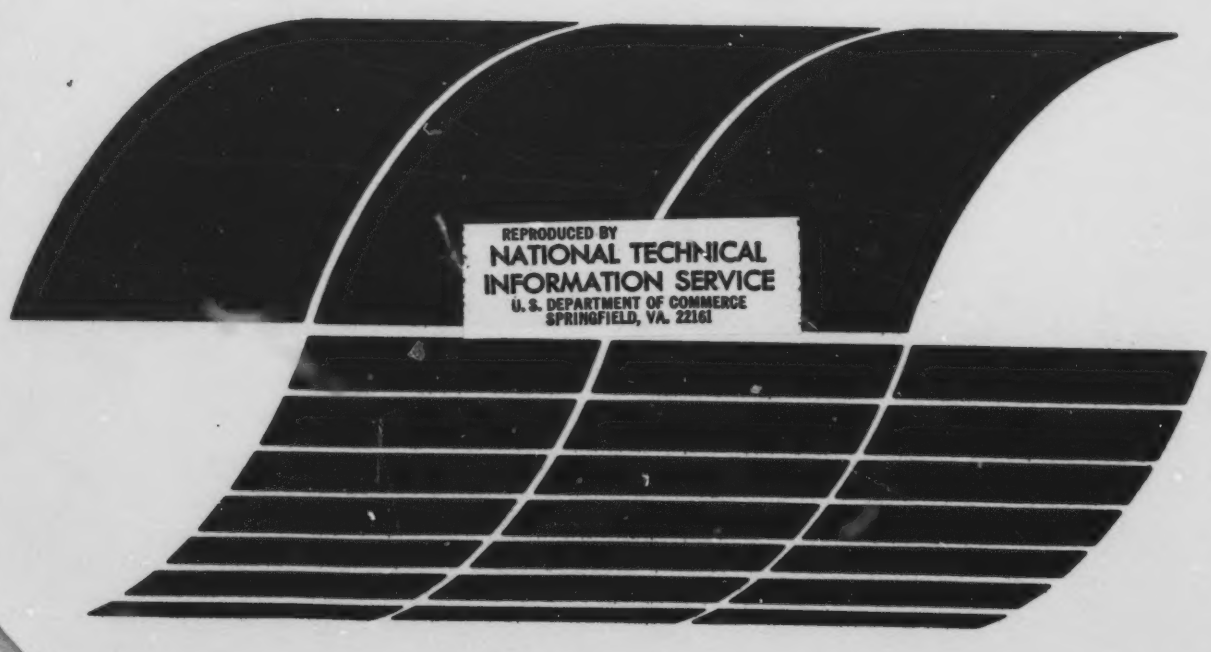

less SO_2 at the inlet and outlet, however fluctuations in the sulfur content of the coal are more than enough to account for the observed change in SO_2 concentration.

Coal samples were analyzed for the conditioned and baseline tests. The sulfur content averaged 1.1 wt % during the conditioned tests and 0.8 wt % during the baseline tests. Otherwise, the samples were very similar with about 11 wt % ash and very low levels of alkali metals (Na, K, Li, Ca).

CONCLUSIONS

The results of this field test clearly indicate that the SO_3 flue gas conditioning system successfully increased the ESP efficiency from about 80% to near the design efficiency of 95% when low sulfur coal fly ash is being collected. The mechanism for improvement appears to be, at least in part, a decrease in fly ash resistivity. This is consistent with the observation of a higher sparking rate during the baseline tests.

The grade efficiency curves indicate a more pronounced improvement in collection of large particles. This could be the result of a reduction in reentrainment associated with use of the conditioning agent.

There was no significant change in SO_2 concentration associated with use of the SO_3 conditioning system. Observed SO_2 fluctuations could be accounted for by variations in the sulfur content of the coal. The sulfur content of the fly ash and the outlet concentration of SO_3 increased significantly when the conditioning agent was injected.

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by

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Office of Research and Development
Washington, DC 20460

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ABSTRACT

A field performance test has been conducted on an electrostatic precipitator (ESP) which uses sulfur trioxide as the conditioning agent. The ESP is located at an electric utilities power plant, burning approximately 1% sulfur coal.

Tests were conducted with and without injection of the conditioning agent. The ESP performance was characterized in terms of particle collection efficiency and the chemical composition of particulate and gaseous emissions. Fly ash resistivity and duct opacity were also measured.

Results show an average increase in overall efficiency from 80% to 95% with injection of the conditioning agent. This is accompanied by a decrease in fly ash resistivity, a decrease in opacity, and an increase in sulfur trioxide concentration entering and leaving the precipitator.

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SECTION 1

INTRODUCTION

The Particulate Technology Branch of the U.S. EPA Industrial Environmental Research Laboratory, Research Triangle Park, NC has contracted with A.P.T., Inc. to conduct a series of field test performance evaluations of electrostatic precipitators (ESP) which use flue gas conditioning agents to improve their performance. This report presents the results of the first field test conducted at an electric utilities power plant which burns low sulfur coal. Sulfur trioxide injection is used to condition the flue gas before it enters the electrostatic precipitator.

Flue gas conditioning agents are used primarily for maintaining high particulate collection efficiency in electrostatic precipitators operating on high electrical resistivity fly ash resulting from the combustion of low sulfur coals. Flue gas conditioning is not usually designed into a new installation but rather is used as a corrective measure for a precipitator which is unable to meet emission or opacity standards.

Many potential conditioning agents have been investigated and a number are available commercially. Conditioning agents may be injected in the boiler or may be injected downstream from the air preheater. Their effectiveness will depend to some extent on the flue gas composition and temperature.

The improved collection efficiency associated with flue gas conditioning generally is attributed to a decrease in the fly ash electrical resistivity. However, other mechanisms such as an increase in space charge and a reduction in rapping reentrainment losses may be more important than resistivity in some situations.

This test program is being conducted to obtain an extensive data base for evaluating the effectiveness of various conditioning agents. It is planned that each test will provide sufficient data to identify the important mechanisms in effect and to quantify any additional process emissions which result from the use of the conditioning system.

SECTION 2

SUMMARY AND CONCLUSIONS

A field performance test has been conducted on an ESP which uses sulfur trioxide injection for flue gas conditioning. The ESP is located at an electric utilities power plant, burning approximately 1% sulfur coal.

Tests were conducted with and without injection of the conditioning agent. The ESP performance was characterized in terms of overall and grade particle collection efficiency and the chemical composition of particulate and gaseous emissions. Fly ash resistivity and in-stack opacity were also measured.

RESULTS

The ESP has a design efficiency of 95% when burning high sulfur coal. When low sulfur coal is burned, the precipitator cannot maintain its design efficiency without gas conditioning. During the unconditioned tests it was observed that sparking was much more frequent than during the conditioned tests.

The overall and grade collection efficiencies were determined from particle size and mass data obtained using in-stack cascade impactors. Overall efficiencies were also obtained using a modification of EPA Method 5. The overall mass efficiency when SO_3 injection was used for gas conditioning averaged 94.9%. Without SO_3 injection, the average efficiency decreased to 80.2%. The grade penetration curves showed improved collection for all particle sizes measured (from about 0.3 to 5 μm dia.) when the conditioning agent was used. However, the improvement appears to be more pronounced for the larger particle sizes.

The measured overall and grade efficiencies compared well with the ESP performance model (Sparks, 1978) for conditioned and baseline tests.

Elemental analyses of certain cascade impactor particulate samples (outlet only) were conducted for the conditioned and baseline tests. The conditioned tests showed an increase in the mass of sulfur leaving the ESP as particulate (2.5 mg/DNm^3) relative to the baseline tests (0.4 mg/DNm^3). Mass emissions of all other elements analyzed were lower in the conditioned tests than in the baseline tests. This is consistent with the lower overall penetration measured for the conditioned tests.

In-situ fly ash electrical resistivity was measured using a point-to-plane probe at the ESP inlet for the baseline and conditioned tests. The average resistivity for the baseline case was 1.7×10^{11} Ω-cm. When SO_3 conditioning was used, the average resistivity decreased to 4.7×10^{10} Ω-cm.

The opacity of the flue gas was measured in the outlet duct of the ESP for the conditioned and baseline tests. The average opacity was 40% during the conditioned tests and 80% during the baseline tests.

Sulfur trioxide concentrations were determined at the ESP inlet and outlet using the controlled condensation method (Maddelone, 1977). The average SO_3 concentration during the conditioned tests was 10.9 ppm at the inlet and 8.1 ppm at the outlet. Theoretically, from a material balance, 32 ppm of SO_3 were injected. The equivalent of approximately 24 ppm SO_3 was accounted for on the fly ash. During the baseline tests the SO_3 concentration averaged 1.6 ppm at the inlet and 1.0 ppm at the outlet. The sulfur content of the fly ash leaving the ESP decreased from 2.5 mg/DNm^3 for the conditioned tests to 0.4 mg/DNm^3 for the baseline tests.

The SO_2 concentration in the flue gas varied from about 650 to 800 ppm at the inlet and from about 600 to 700 ppm at the outlet. The lower concentration at the outlet may have been caused by in-leakage of air. This hypothesis is consistent with an observed increase in O_2 concentration at the outlet. The unconditioned (baseline) tests showed about 13%

SECTION 3

DESCRIPTION OF TEST

PLANT DESIGN

The plant has six power generating units and a seventh unit under construction. Testing was performed on unit No. 3 which has a boiler rated at 44 megawatts. Unit No. 3 has a maximum operating capacity of 58 megawatts producing 10,000 kPa (1,450 psi) steam at 540°C (1,005°F). The location of the SO_3 injection ports, and inlet and outlet sampling ports is shown in Figure 1.

The ESP, installed downstream from the air preheater (Ljüngstrom type), has a design efficiency of 95% when burning high sulfur coal. It is preceded by a bank of axial entry cyclones of undetermined efficiency. The ESP consists of two sections in series; i.e., an inlet and an outlet section. Each has a transformer-rectifier (T/R) set which can be electrically isolated into a right and left subsection. The wire current is full wave rectified. Design information for the ESP is given in Table 1.

The configuration of the precipitator can be seen in Figure 1. The flue gas flows through the axial entry cyclones where it is directed upward past the SO_3 injection nozzles into a bend with turning vanes. There is a diverging section immediately before the ESP. Downstream from the ESP the flue gas converges and is directed upward and over the top of the precipitator to the induced draft fan. Turning vanes are provided to improve flow distribution.

The eight inlet sampling ports are at the upstream edge of the diverging section before the ESP. The four outlet ports are located immediately following the bend over the precipitator.

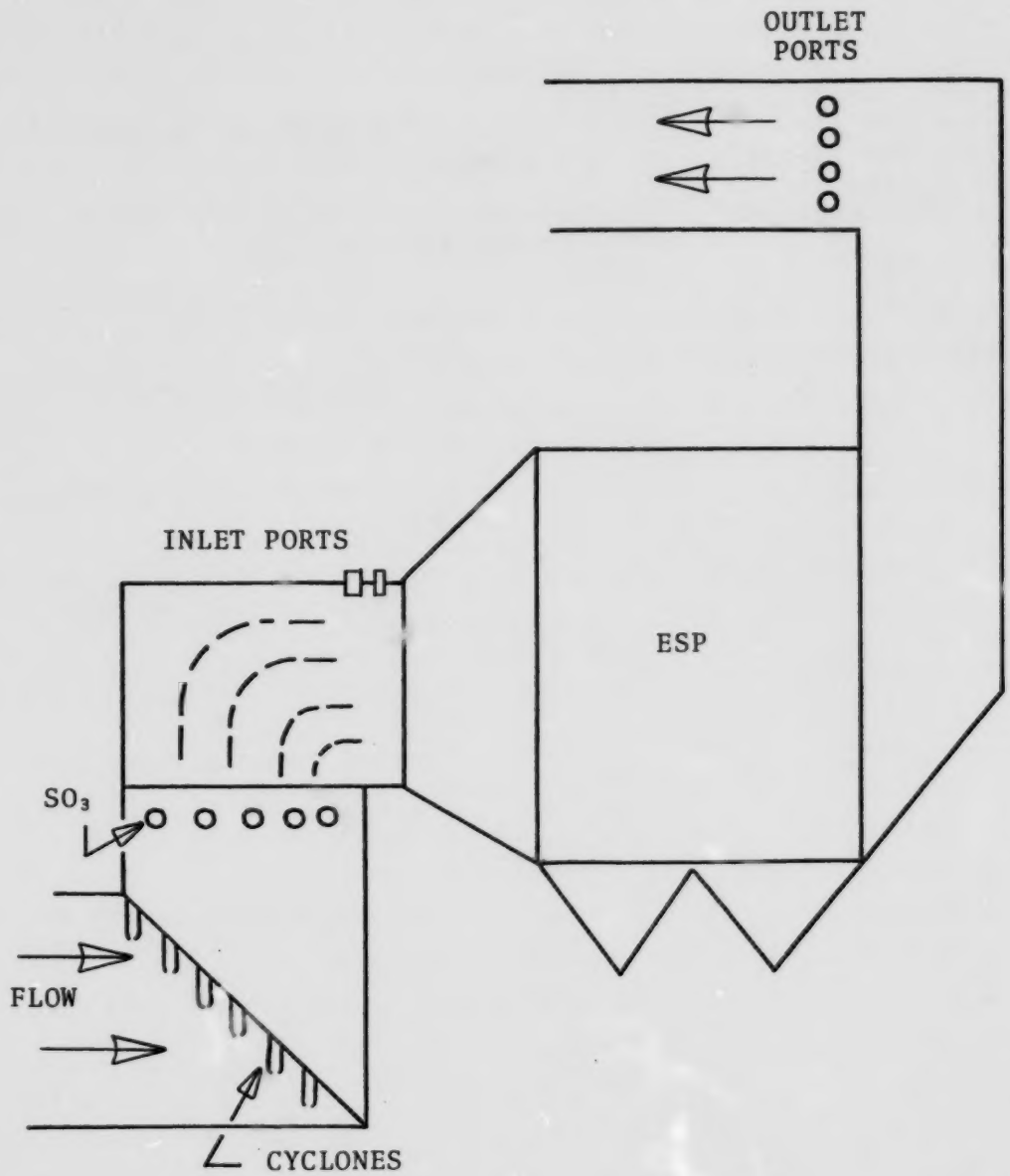

Figure 1. Plant layout.

TABLE 1. ELECTROSTATIC PRECIPITATOR DESIGN INFORMATION

Startup date	1972
Design gas flow	104 actual m^3/s (217,000 actual ft^3/min)
Design gas velocity	1.05 m/s (3.4 ft/s)
Design specific collector area	36 m^2 per actual m^3/s (182 ft^2 per 1000 actual ft^3/min)
Design efficiency	95%
Precipitation rate	W_e - 0.084 m/s (0.274 ft/s)
Overall configuration	2 series chambers 3 electrical sections in parallel per chamber 36 parallel gas passages
Plates	37 plates per chamber (cold rolled steel sheets) plate height - 9.5 m (31 ft) plate length each section - 2.7 m (9 ft) for total length in direction of flow of 5.5 m (18 ft) plate-to-plate spacing - 0.23 m (9 in.) total surface area of plates - 3,730 m^2 (40,180 ft^2)
Wires	12 equally spaced wires per gas passage wire diameter - 2.8 mm (0.11 in.) wires are hanging type, placed in the center ±6.4 mm (1/4 in.) of the plate-plate space
Electrical	2 transformer-rectifier sets which were electrically insolatable into 6 subsections maximum power consumption - ~50 kW

Fly ash is removed from the wires and plates by vibrators which operate for about one minute every five minutes. The collected ash falls into hoppers beneath the ESP. The manually activated ash handling system pulls the ash from the hoppers with suction from a water ejector nozzle and deposits it in a silo. The silo is emptied by truck.

The SO_3 injection system converts hot vaporized SO_2 and air into SO_3 over a vanadium pentoxide (VO_5) catalyst. It is injected into the flue gas downstream from the air preheater and cyclone at 490°C (920°F) through five rows of nozzles. The flue gas is approximately 160°C (320°F) at the injection point. The SO_2 is stored in bulk liquid form and consumed at a constant rate of approximately 46 lbs/hr at full load of 58 MW. For 100% conversion of SO_2 to SO_3, this corresponds to a maximum addition of 32 ppm of SO_3 to the flue gas stream.

OPERATING CONDITIONS

The unit was operated at full load for the duration of the test. It was controlled to produce a constant steam rate. Full load was limited by the air intake dampers. The maximum design flow of the ESP was 104 m^3/s (217,000 ACFM). The flow during the test was slightly lower at 102 m^3/s (217,000 ACFM). As can be seen from Table 2, the power output of the plant increased on January 31. This was caused by chlorination of the condensers; a cleaning operation which makes the condensers more efficient, thus enabling higher output from the turbines for the same steam rate.

Voltage current relationships were determined for the ESP during both the conditioned and baseline test periods (Figures 2 and 3). The normal operating point at both the inlet and outlet of the ESP was a voltage of 50 kV and a current density of 24 nA/cm^2. The test data were generated by adjusting the primary voltage manually and recording the resulting primary and secondary currents. A secondary voltage meter was not available so that secondary voltage had to be calculated from the power transmitted that is:

TABLE 2. BOILER LOAD DATA

Date	Boiler Load MW
1/25/78	57.5
1/26/78	57.5
1/27/78	57.5
1/31/78	58.5
2/1/78	58.5
2/5/78	58.5
2/6/78	58.4
2/7/78	58.4

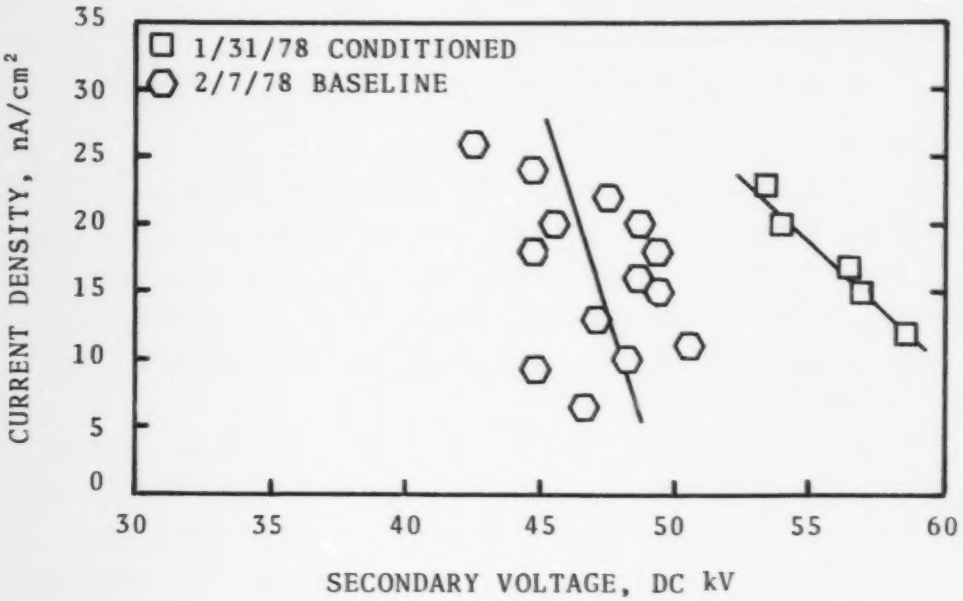

Figure 2. ESP inlet section voltage-current relationships.

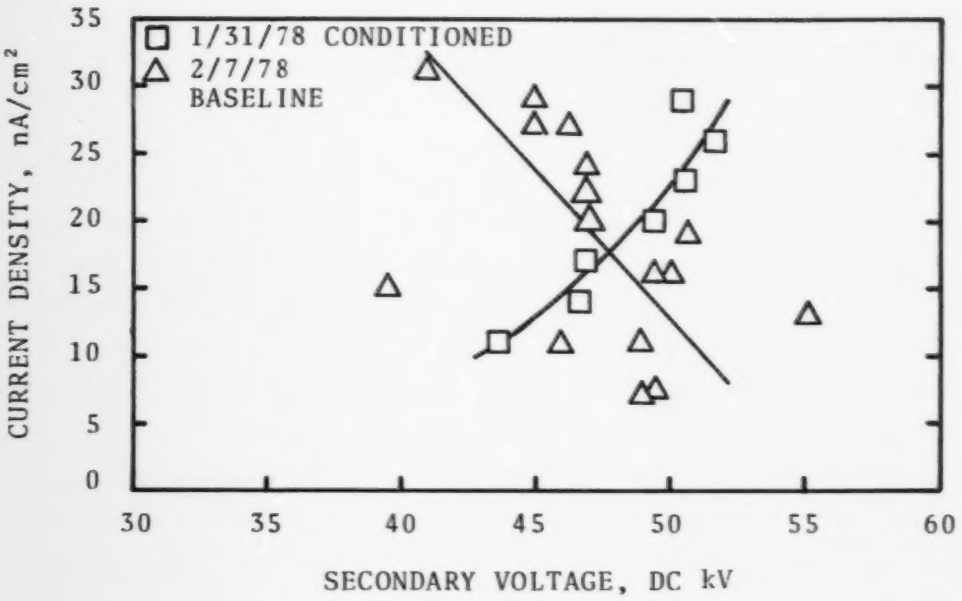

Figure 3. ESP outlet section voltage-current relationships.

$$V_2 = 0.85 \frac{V_1 I_1}{I_2} \quad (1)$$

where V_1 & V_2 = primary and secondary voltages, V
I_1 & I_2 = primary and secondary currents, A
0.85 = efficiency assumed for the transformer-rectifier set

Two factors contribute to the scatter of data on the curves: 1) sparking, particularly during the unconditioned (baseline) tests, made the meters jump continually so that they were very difficult to read accurately; 2) the lack of a secondary voltage meter necessitated calculations which multiplied the errors inherent in the meter readings.

The current-voltage relationships for the inlet and outlet sections of the ESP are shown in Figures 2 and 3, respectively. The solid lines represent least squares fits to the data. The inlet section shows a marked shift to the right for the conditioned case compared to the baseline case. This shift implies a higher operating voltage is possible for a given current when the conditioning agent is used. This is consistent with the effect anticipated with a decrease in fly ash resistivity. The outlet section (Figure 3) does not show any clear trends.

No spark meter was available but the sparking was clearly increased during the unconditioned case. Sparking persisted to the lowest secondary voltage.

TEST METHODS AND SCHEDULE

Field tests of the ESP were conducted with and without injection of the flue gas conditioning agent. Variances were obtained from the proper agencies for periods covering the unconditioned tests.

The field test spanned the period January 25 to February 7, 1978. Testing of the conditioned case started on January 25 and ended on February 2. The boiler unit was shut down three days for boiler tube repairs (January 28, 29, 30) during this time.

A three-day deconditioning period allowed the ESP to come to steady state before the baseline (unconditioned) tests, which started February 5 and lasted through February 7.

The particulate analyses included size, mass, resistivity and chemical composition. Size distributions were obtained at the inlet and the outlet of the ESP with calibrated cascade impactors. A modified EPA Method 5 train was used for total mass determinations.

The resistivity of the particulate fly ash entering the ESP was monitored with an in-situ point-to-plane resistivity probe. Plume opacity in the outlet duct of the ESP was measured using a modified opacity meter and was recorded on a continuous basis.

Coal samples were obtained daily and analyzed to characterize the coal composition during the testing period.

Information on the ESP design, maintenance and operation were obtained from power plant personnel through survey forms and personal communications. The current-voltage relationships for each section of the ESP were determined for conditioned and unconditioned tests. Annual operating and maintenance costs were obtained for the ESP, flue gas conditioning equipment and chemicals.

Samples of particulate matter collected with a cascade impactor at the ESP inlet and outlet were analyzed to determine the elemental composition as a function of particle size. The amount of particulate sulfate collected on the impactor substrates was determined with an acid-base titration using bromophenol blue as the indicator. Ion excited X-ray emission analysis was used to determine the elemental composition.

The flue gas velocity and static pressure were measured at the inlet and outlet using calibrated S-type pitot tubes. The molecular weight and density of the gas was determined by measuring the gas composition and temperature. The concentration of water vapor was determined from measurements of the wet and dry bulb temperature in the stack.

SO_2 concentrations entering and leaving the ESP were determined using a Du Pont SO_2 stack analyzer (model 459). The output from the SO_2 analyzer was recorded on a continuous basis during the field test.

The concentration of SO_3 entering and leaving the ESP was determined with the controlled condensation method as described by Maddelone (1977).

SECTION 4

TEST RESULTS

COLLECTION EFFICIENCY

Overall and fractional collection efficiencies were determined from particle size and mass data obtained using in-stack cascade impactors. Overall efficiencies were also obtained using a modification of EPA Method 5 (M5). The sampling trains and procedures are presented in Appendix "A".

Particle size distributions at the ESP inlet are presented in Figures 4 and 5 for the conditioned and baseline tests, respectively. The inlet size distributions were very consistent with a geometric mass median diameter (MMD) of 8.5 μm* and a geometric standard deviation of about 4.

The size distributions at the ESP outlet are presented in Figures 6 and 7 for the conditioned and baseline tests. The outlet particles were smaller for the conditioned tests (MMD = 2.2 μm, σ_g = 3.7) than for the baseline tests (MMD = 3.7 μm, σ_g = 4.1).

A summary of the overall efficiencies is presented in Table 3. The modified M5 test results give somewhat higher mass loadings than do the impactor results. Inlet run "2-M5" is suspect because the nozzle tip may have contacted a layer of fly ash on the bottom of the duct. The average efficiency data show an increase from 80.2% to 94.9% associated with injection of the conditioning agent.

* The convention used in this report is that physical particle diameters are shown as μm and aerodynamic particle diameters are shown as μmA. The physical particle diameter is related to the aerodynamic particle diameter by:

$$d_{pa} = d_p \, (\rho_p \, C')^{\frac{1}{2}}$$

where d_{pa} = aerodynamic particle diameter, μmA; ρ_p = particle density, g/cm^3
d_p = physical particle diameter, μm; C' = Cunningham slip correction factor, dimensionless

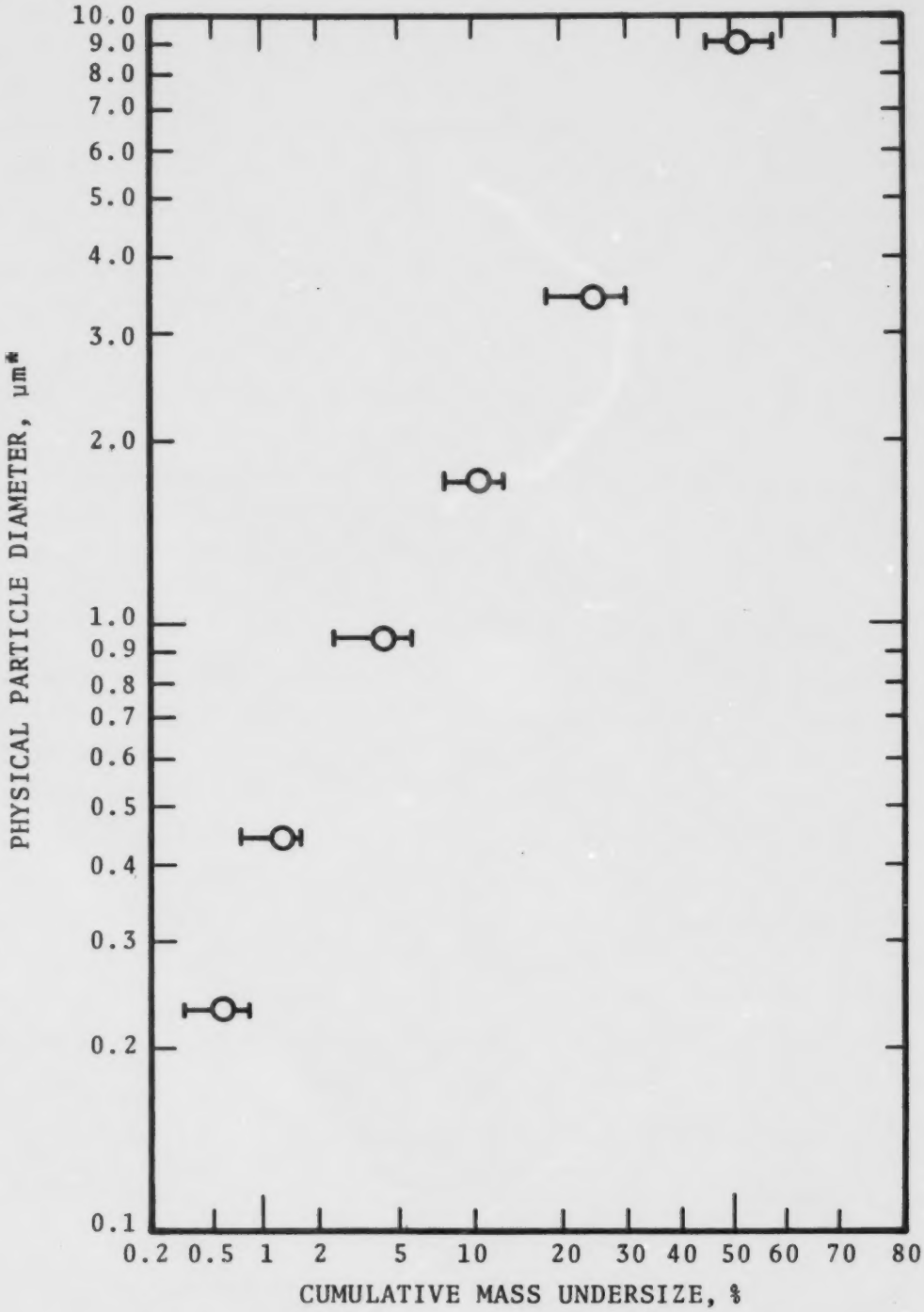

Figure 4. Inlet size distribution for conditioned tests showing 90% confidence intervals.

* Density assumed to be 2.3 g/cm^3

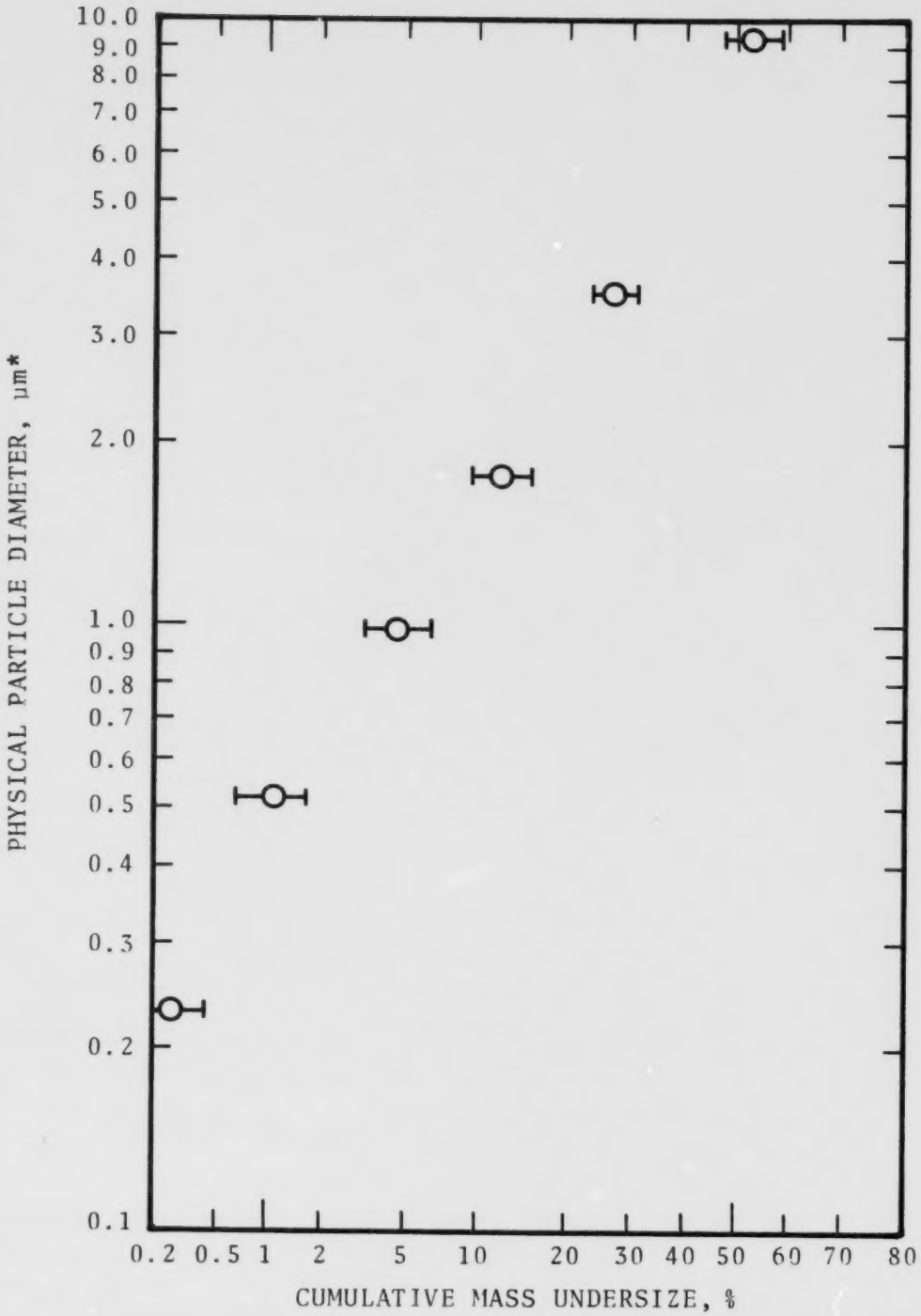

Figure 5. Inlet size distribution for baseline tests showing 90% confidence intervals.

* Density assumed to be 2.3 g/cm^3

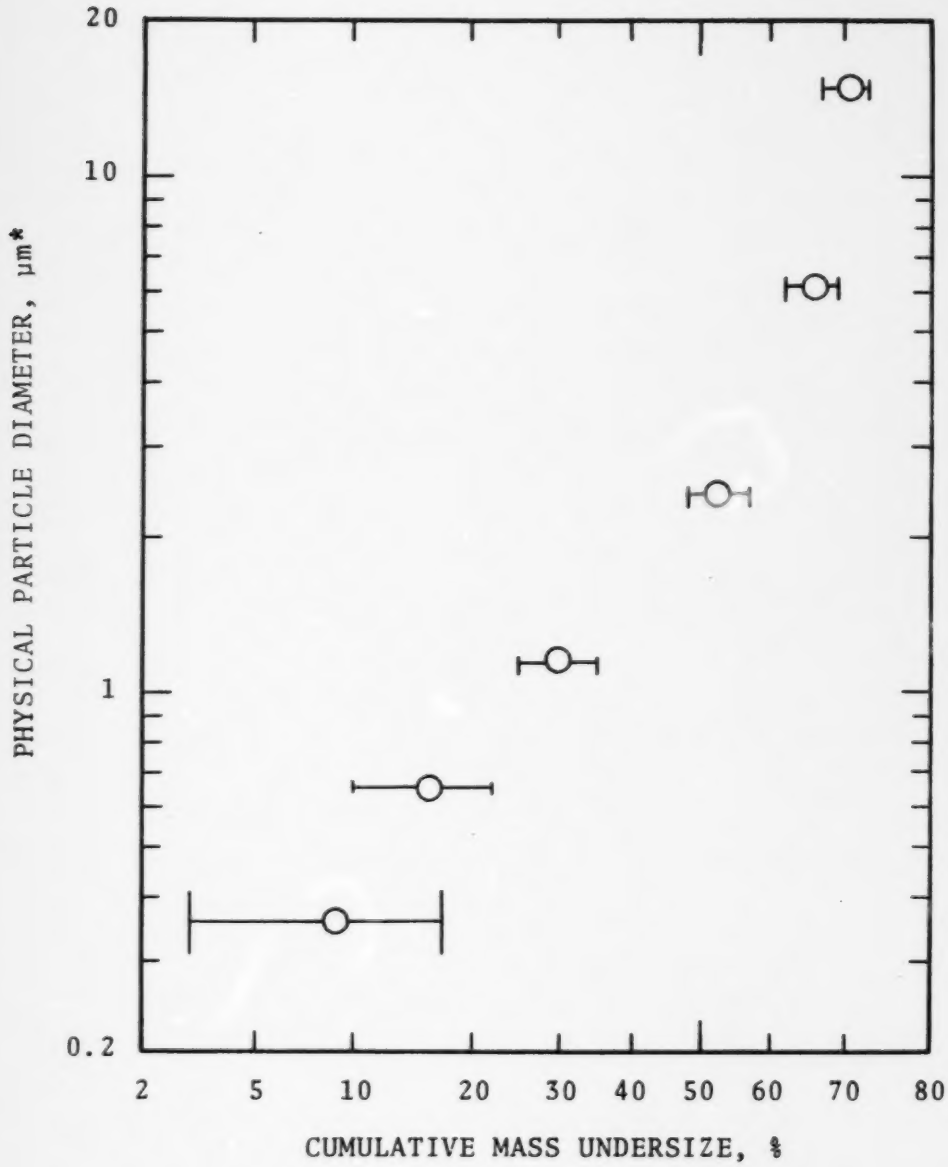

Figure 6. Outlet size distribution for conditioned tests showing 90% confidence intervals.

* Density assumed to be 2.3 g/cm^3

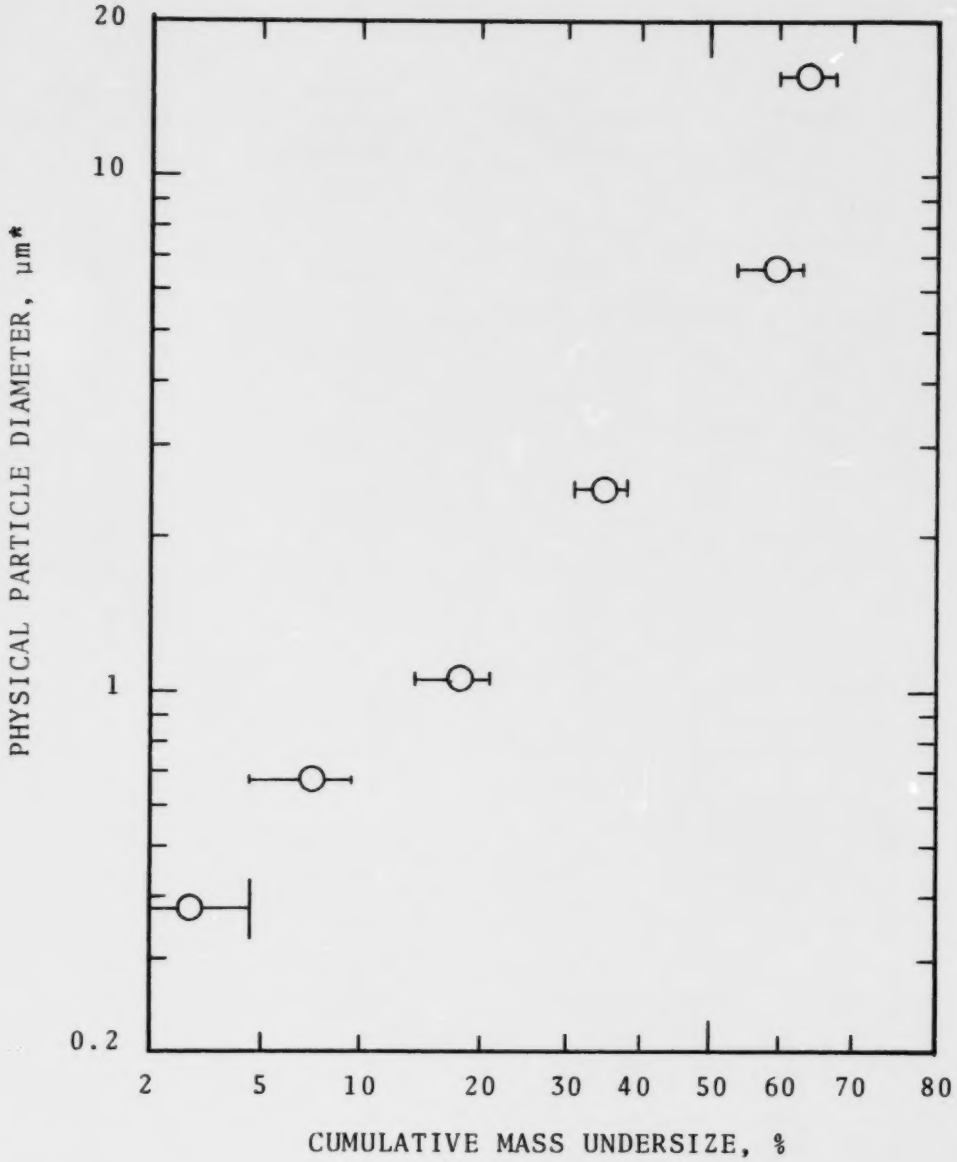

Figure 7. Outlet size distribution for baseline tests showing 90% confidence intervals.

* Density assumed to be 2.3 g/cm^3

TABLE 3. SUMMARY OF OVERALL EFFICIENCIES

Run #	Inlet Concentration mg/DNm^3	Outlet Concentration mg/DNm^3	Overall Efficiency %
With SO_3			
1	2,535	104.8	95.9
2	2,500	105.3	95.8
12	2,375	127.9	94.6
13	2,605	145.1	94.4
14	2,525	136.3	94.6
16	3,139	101.4	96.8
1-M5*	2,289	265.6	88.4
2-M5*	12,590	208.3	98.3
Average			94.9
Standard Deviation			2.9
Without SO_3			
17	2,297	588.3	74.4
21	2,470	428.2	82.7
23	2,483	503.3	79.7
24	2,595	514.1	80.2
26	2,449	426.6	82.6
28	2,154	510.2	76.3
3-M5*	4,179	605.5	85.5
Average			80.2
Standard Deviation			3.8

* Modified EPA Method 5

Grade penetration curves were computed from the simultaneous inlet and outlet test data. The computation was based on a logarithmic spline fit to the cumulative mass concentration curves obtained from the cascade impactor data (Lawless, 1978). The results are presented as Figures 8 and 9.

The conditioned tests show considerably lower penetration (higher efficiency) than the baseline tests. The improvement is particularly apparent for large particles.

Each day one impactor run was made to collect a particulate sample for sulfate analysis. The fly ash on the substrate was analyzed with an acid/base titration using Bromophenol Blue as the indicator. The results showed the sulfate concentration to be below the detectable limit of 1 ppm. One exception was the final filter of the outlet impactor which showed measurable amounts of $SO_4^=$ on some runs. However, this may have been an artifact resulting from condensation of moisture in the probe. Moisture which collected on the probe wall may have contained sulfate ions. When the sampling ended, the liquid could have drained down to the final filter as the probe was being withdrawn. The final filter was wet after some runs. The detailed table of results is presented in Appendix "C".

ESP PERFORMANCE PREDICTIONS

Performance of the precipitator was predicted using a calculator program which models ESP performance (Sparks, 1978). The predicted performance is based on a model developed by Southern Research Institute (Gooch, 1975). The predicted baseline overall efficiency of the ESP is 79.9%, which compares with the measured value of 80.8%. When the resistivity of the fly ash is reduced to the conditioned level of 4.7×10^{10} Ω-cm, the predicted overall efficiency is 92.9%. The measured overall efficiency was 94.9%

Grade penetration curves were calculated with the program and are shown in Figures 8 and 9. These figures show a slightly higher penetration than the measured values.

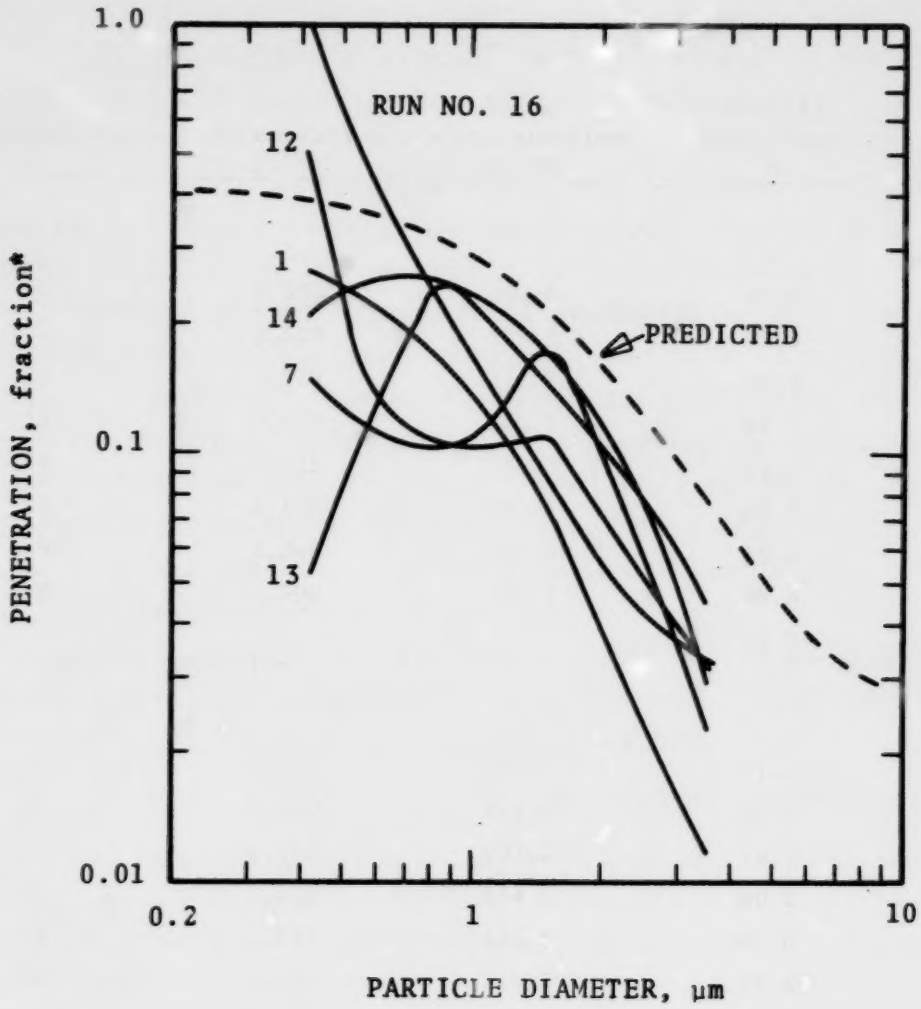

Figure 8. Grade penetration curves for SO_3 conditioned tests.

* Density assumed to be 2.3 g/cm³

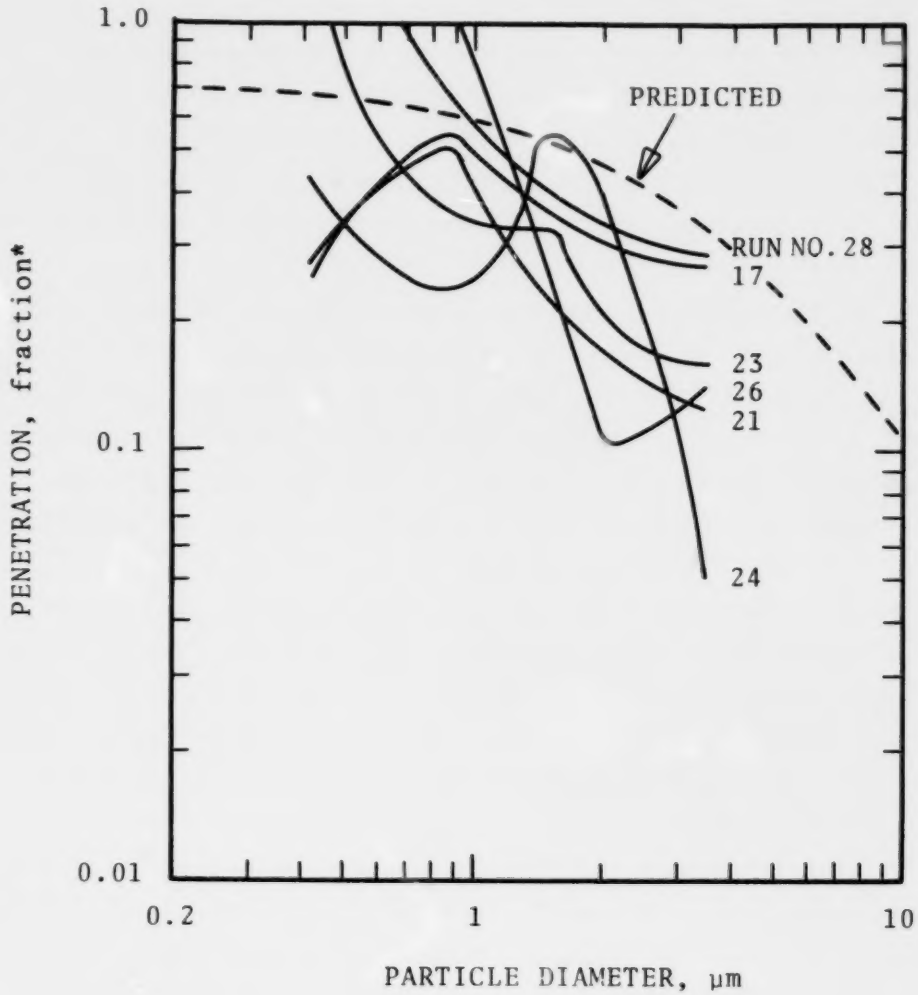

Figure 9. Grade penetration curves for baseline tests.

* Density assumed to be 2.3 g/cm^3

The parameters input to the program are derived from data obtained during the test period. These are shown in Table D-1 in Appendix "D".

FLUE GAS COMPOSITION

The flue gases were sampled with an Orsat analyzer, a Du Pont SO_2 analyzer and a controlled condensation sulfate system (CCS). The CCS was used to measure the quantity of SO_3.

Flue gas velocity was determined with calibrated S-type pitot tubes. The velocity was measured at 48 points over the cross-section of the ducts. The velocity varied erratically over the test period at both inlet and outlet, as shown in Table 4. This may have been caused by turbulence from the downstream turning vanes.

The concentrations of O_2, CO_2, H_2O, and SO_2 are shown in Tables 4 and 5 for the inlet and outlet. The O_2 concentration is higher at the outlet (Table 5) than the inlet (Table 4). Discrepancies may be attributed to in-leakage of air since the ESP operates at a negative pressure of 3.2 kPa (13" W.C.). Using the average O_2 concentrations, an in-leakage rate of 7.5% was computed between the inlet and outlet of the ESP. This compares well with the leakage rate computed by comparing SO_2 concentrations.

The concentrations of SO_3 entering and leaving the ESP was determined by the controlled condensation system (CCS) as described by Maddelone (1977). A schematic of the CCS is shown in Figure 10. This method is designed to operate at high temperature. The sampling probe is maintained at a temperature of 315°C (600°F) and the quartz filter holder is heated by a heating mantle so that a gas outlet temperature of 290°C (550°F) is maintained. This temperature is required to ensure that H_2SO_4 will not condense in the filter holder. The separation of SO_3 from SO_2 is achieved by cooling the gas stream below the dew point of H_2SO_4 but above the H_2O dew point, thus preventing interference from SO_2. The condensed acid was then titrated with 0.2 N NaOH using Bromophenol Blue as the indicator.

The probe nozzle was turned downstream during the sampling period to reduce the quantity of large particles reaching the

TABLE 4. ESP INLET FLUE GAS CONDITIONS (DAILY AVERAGE)

Date	Flue Gas Temperature °C	Flue Gas Composition, Vol./Vol. $\%O_2$	$\%CO_2$	$\%H_2O$	SO_2 ppm	Average Velocity m/s
1/25/78	142	--	--	6.1	730	5.8
1/26/78	139	--	--	5.5	710	5.2
1/27/78	145	--	--	6.6	720	5.0
1/31/78	133	4.4	14.1	4.0	730	5.9
2/1/78	146	3.9	14.6	4.5	840	5.5
2/5/78	135	5.0	14.0	5.6	650	5.7
2/6/78	147	4.5	14.2	4.4	680	5.2
2/7/78	--	4.7	14.2	--	670	--

TABLE 5. ESP OUTLET FLUE GAS CONDITIONS (DAILY AVERAGE)

Date	Flue Gas Temperature °C	Flue Gas Composition, Vol./Vol. $\%O_2$	$\%CO_2$	$\%H_2O$	SO_2 ppm	Average Velocity m/s
1/25/78	144	--	--	2.2	700	8.8
1/26/78	--	--	--	6.2	650	8.9
1/27/78	145	--	--	4.0	660	9.2
1/31/78	147	--	--	4.9	680	9.6
2/1/78	152	5.3	14.0	5.0	680	8.7
2/5/78	146	--	--	4.8	600	8.8
2/6/78	--	--	--	6.1	620	8.8
2/7/78	--	6.0	13.0	--	620	--

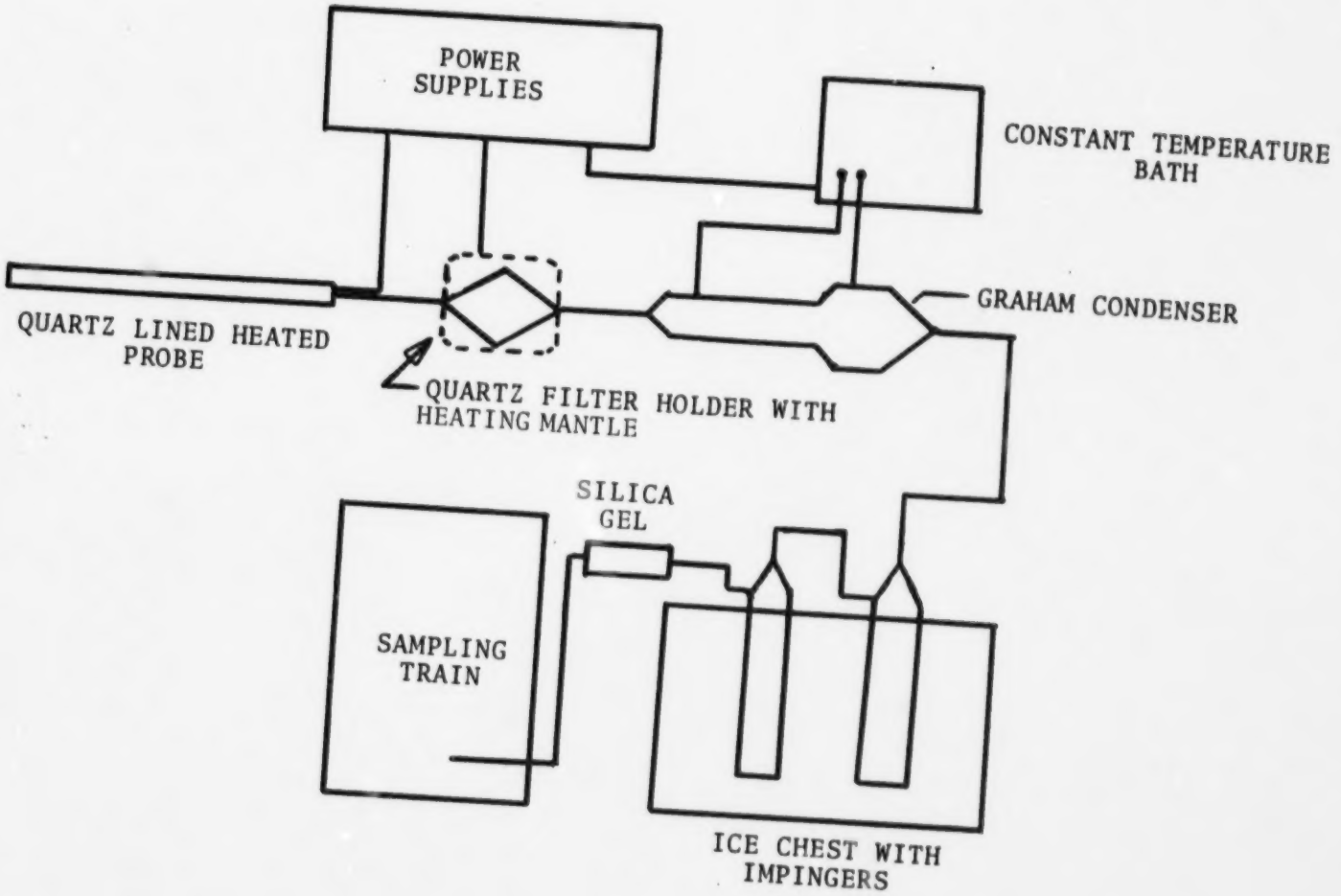

Figure 10. Controlled condensation system.

filter. If the amount of material on the filter is kept small, the overall recovery of the CCS is better.

The results of the CCS analysis are shown in Table 6. The concentration of SO_3 was higher at the inlet in both cases implying that the fly ash is adsorbing SO_3 in the ESP. For the conditioned tests, the measured level of SO_3 was 10.9 ppm at the inlet. This is less than the 32 ppm calculated from the SO_2 injection rate. The remaining sulfate may be on the surface of the fly ash.

SO_2 entering and leaving the ESP was determined using a Du Pont SO_2 stack analyzer (Model 459). The output from the SO_2 analyzer was recorded on a continuous basis during the field test period. The SO_2 analyzer was switched from the ESP inlet to the outlet at one-hour intervals. The inlet SO_2 concentration is plotted for the test period in Figure 11. The conditioned tests show a reasonably steady concentration of 700 to 770 ppm (at the inlet). During the baseline tests the SO_2 concentration was about 670 ppm. The lower SO_2 concentration is most likely a result of the lower sulfur content in the coal during the baseline tests.

ELEMENTAL ANALYSIS

The elemental composition of the particulates at the ESP outlet was determined as a function of particle size. The particulates were collected on 1.0 mil Mylar film substrates coated with Apiezon "L" grease in a cascade impactor. These substrates were then analyzed for chemical composition with proton induced -ray fluorescence (Ensor et al., 1968). Mylar substrates coated with Apiezon "L" grease exhibit a low background of trace elements when analyzed.

The results of the analysis, as received, are shown in Appendix "E". Figures 12 and 13 show the flue gas concentration for the detectable elements with particle size as the parameter. These figures show that the concentration of particulate sulfur increased from 0.4 to 2.5 mg/DNm^3 when the conditioning agent was injected.

TABLE 6. CONCENTRATION OF SO_3 IN FLUE GAS

Run Number	SO_3 Concentration With Conditioning Agent, ppm by vol.		SO_3 Concentration Without Conditioning Agent, ppm by vol.	
	Inlet	Outlet	Inlet	Outlet
1	6.4	*	*	*
2	14.6	5.8	4.4	1.1
3	11.6	8.0	1.6	*
4	*	9.1	1.7	0.7
5	*	9.5	*	0.9
			6 2.0	1.1
			7 1.2	1.0
Avg.	10.9	8.1	2.2	1.0
σ_g	4.1	1.7	1.3	0.2

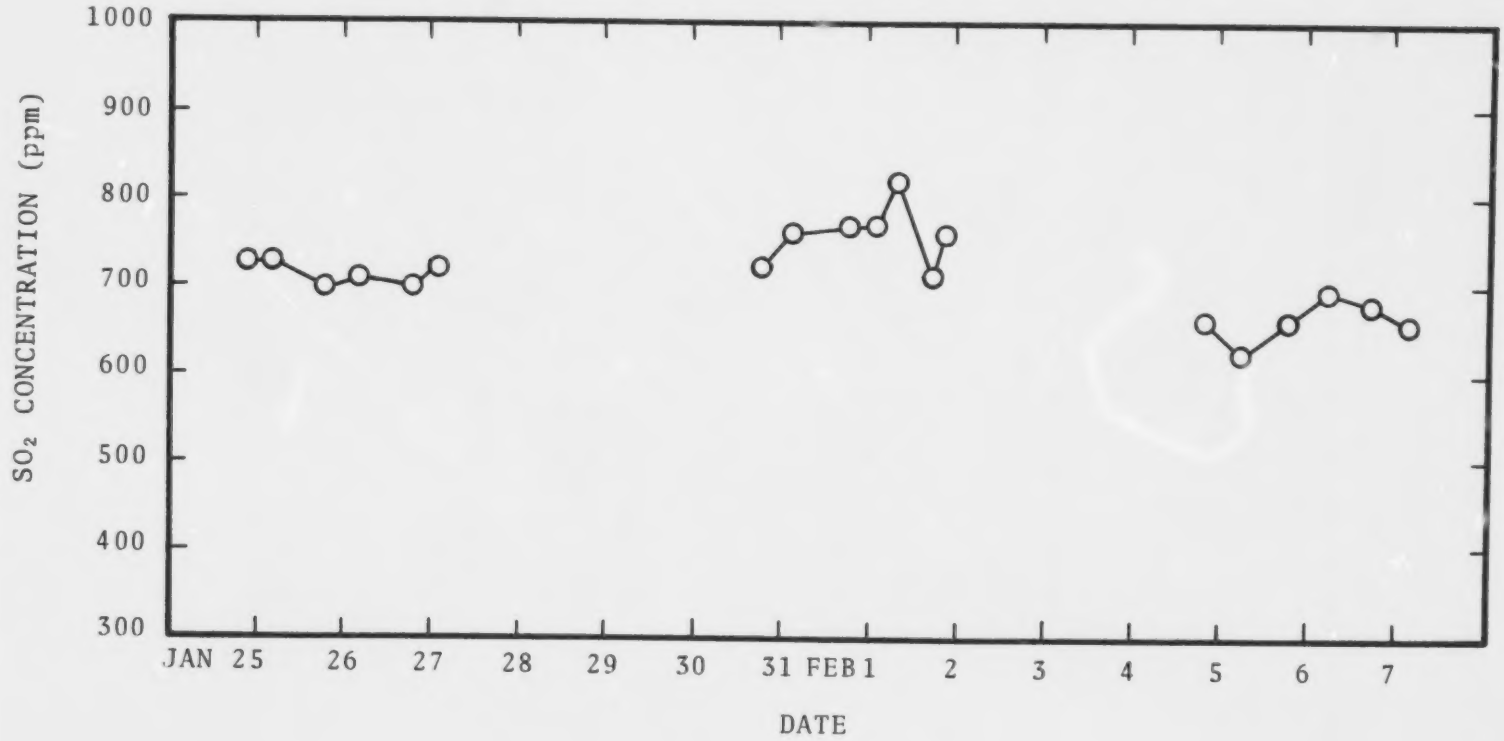

Figure 11. SO_2 concentration of flue gas at ESP inlet.

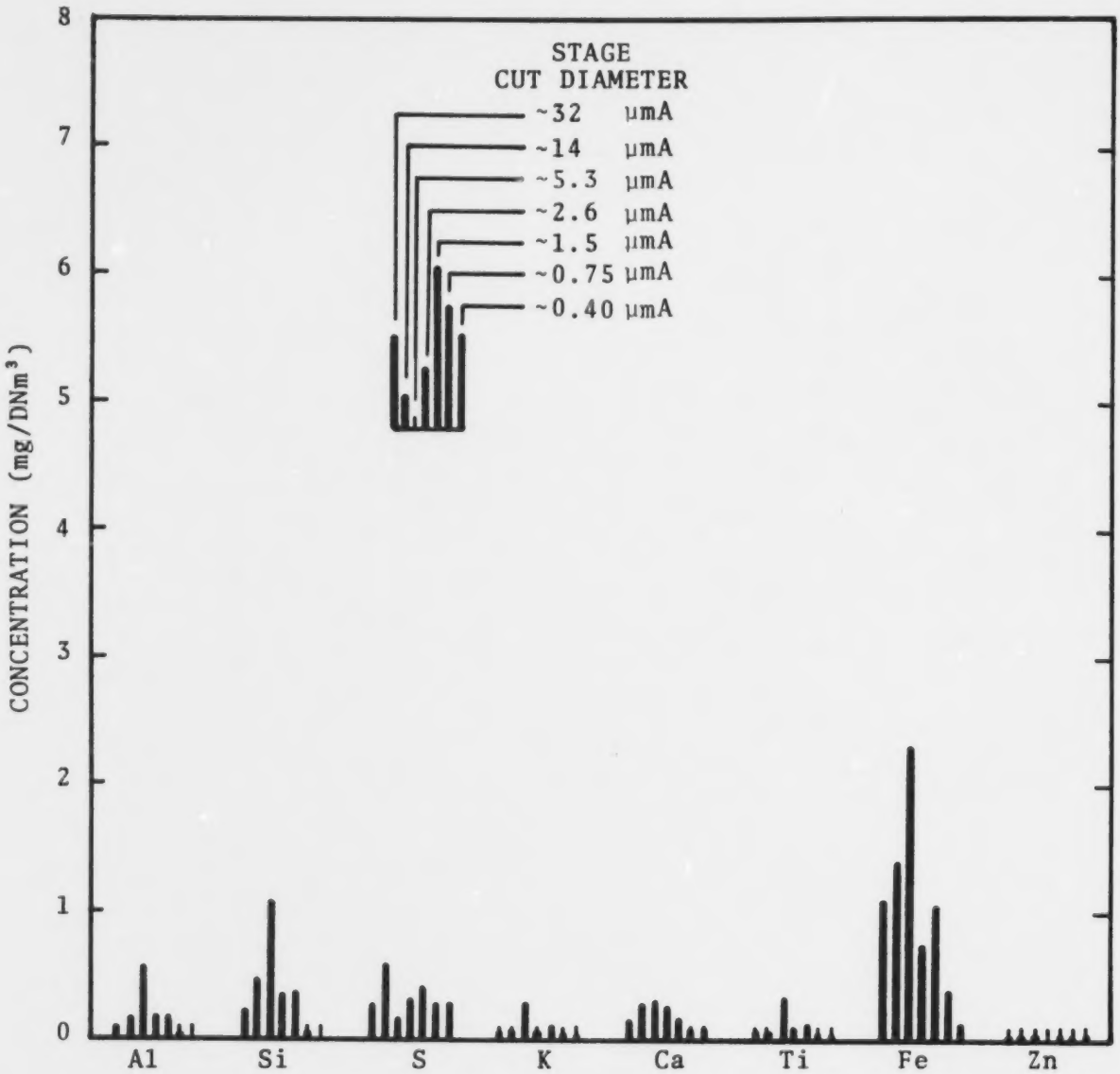

Figure 12. Mass concentrations of major elements in fly ash with SO_3 conditioning.

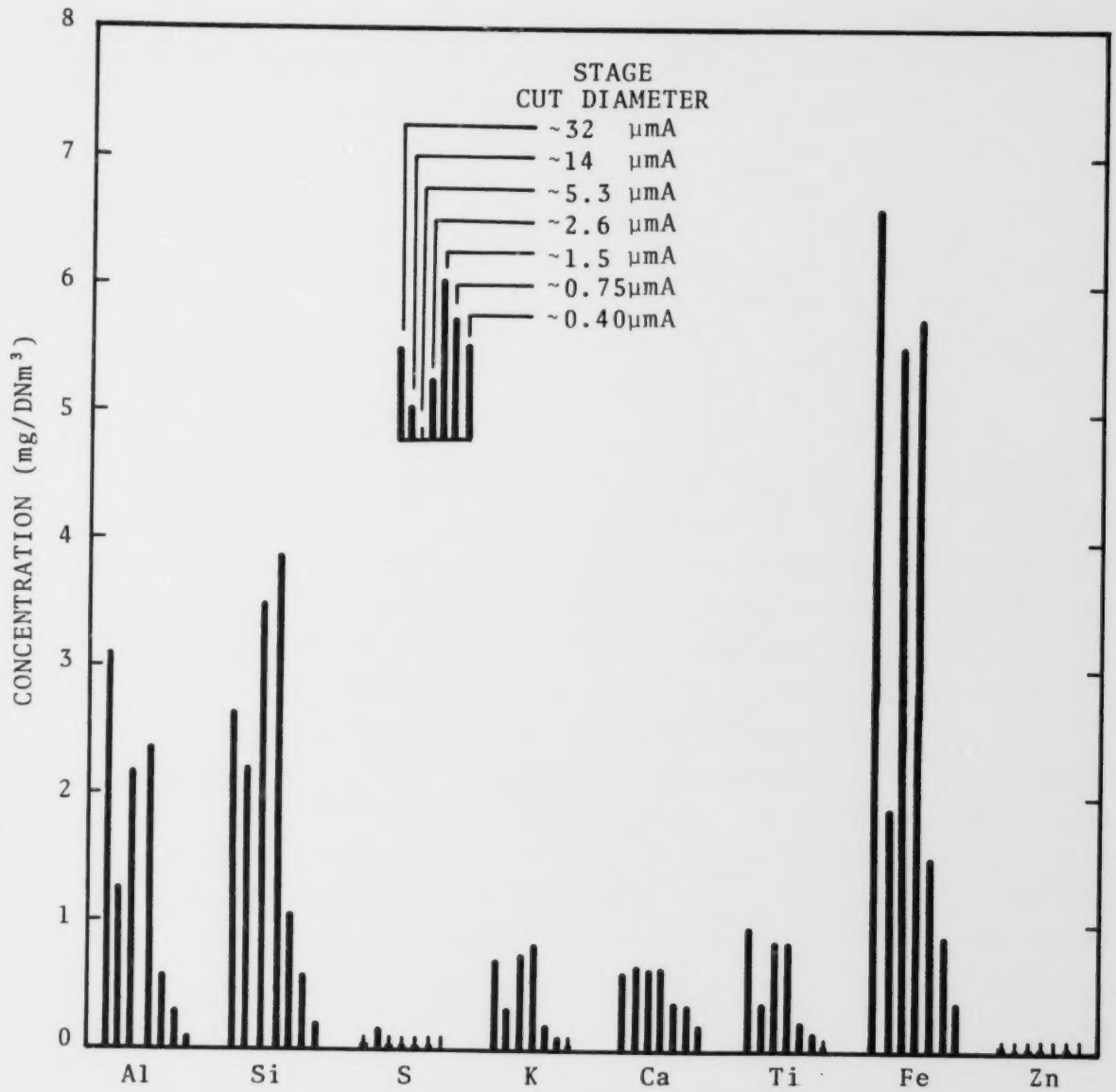

Figure 13. Mass concentrations of major elements in fly ash from baseline test.

RESISTIVITY

Dust resistivity is defined as the resistance of the dust layer to electrical current, measured in Ω-cm. The dust resistivity was measured at the outlet with the Southern Research Institute in-situ point-to-plane resistivity probe (Smith et al., 1977).

The dust resistivity is determined from,

$$\rho = \frac{A}{t}\frac{V}{I} \qquad (2)$$

where ρ = dust resistivity, Ω-cm
A = plate surface area, cm
V = voltage, V
t = dust layer thickness, cm
I = current, A

Table 7 shows the results of the dust resistivity measurements during the conditioned and baseline tests. With SO_3 conditioning, the average resistivity decreased by a factor of four, from 1.7×10^{11} Ω-cm to 4.7×10^{10} Ω-cm.

The corresponding precipitation rate, W_e, increased with the conditioning from 0.05 m/s (0.15 ft/s) to 0.08 m/s (0.27 ft/s). Fly ash resistivity and precipitation rate data from previous field performance tests predicted precipitation rates of 0.05 m/s (0.16 ft/s) and 0.09 m/s (0.28 ft/s) for the above resistivities (White, 1974). The good agreement between observed and predicted values indicates both the representative nature of this test and the functional relationship that exists between resistivity and precipitator efficiency.

OPACITY

The opacity in the outlet duct of the ESP was monitored continuously during the tests with a Lear-Siegler RM4 opacity meter modified for portable use. A schematic of the probe is shown in Figure 14.

TABLE 7. INLET FLY ASH RESISTIVITY

Date	Temperature °C	Temperature (°F)	Resistivity Ω-cm
With conditioning agent			
1/26	121	(250)	3.9×10^{10}
1/27	132	(270)	7.6×10^{10}
1/31	137	(279)	1.5×10^{10}
2/1	139	(283)	5.7×10^{10}
	Average		4.7×10^{10}
	σ_g		2.6×10^{10}
Without conditioning agent			
2/5	133	(272)	1.5×10^{11}
2/5	137	(278)	1.6×10^{11}
2/6	136	(277)	2.0×10^{11}
2/6	137	(278)	1.3×10^{11}
2/7	142	(287)	2.3×10^{11}
2/7	142	(288)	1.7×10^{11}
	Average		1.7×10^{11}
	σ_g		0.4×10^{11}

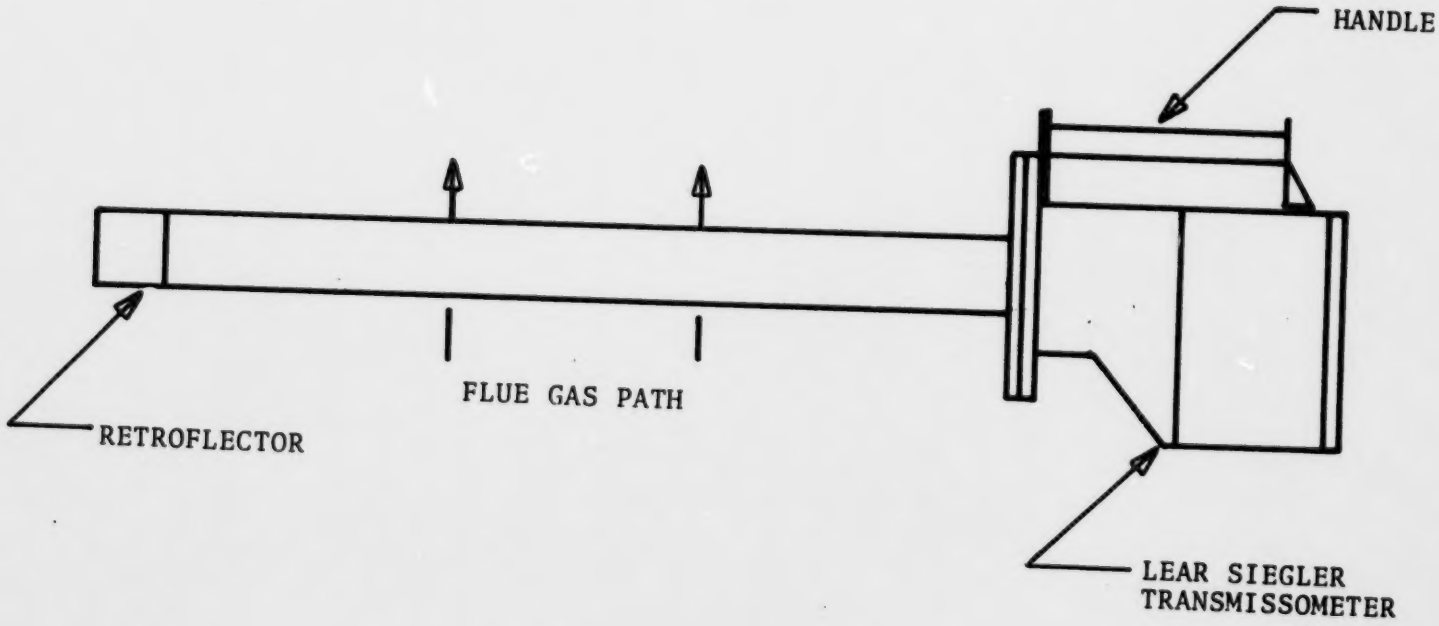

Figure 14. In-stack opacity probe.

During the conditioned test, the opacity was in the range of 40%, as shown in Figure 15. The gap during the conditioned test is from a shutdown of the No. 3 unit. The opacity rose to the limit of the scale set on the opacity meter after injection of the conditioning agent was stopped. After switching to a higher range, the opacity measured approximately 80%.

COAL COMPOSITION

Coal samples were withdrawn from the coal entering the pulverizers every two hours to obtain five or six samples per day. These samples were mixed and a portion taken for analysis. The size of the coal entering the pulverizers ranged from 1 mm to 3 cm in diameter. Plant analyses of the coal were also made available and are included in Table 8.

The sulfur concentrations of the samples taken by A.P.T. show some deviation from plant data. This may be attributable to different sampling times. The conditioned period shows a higher level of sulfur. This increased sulfur content would cause a higher concentration of SO_2 in the flue gas, as was observed.

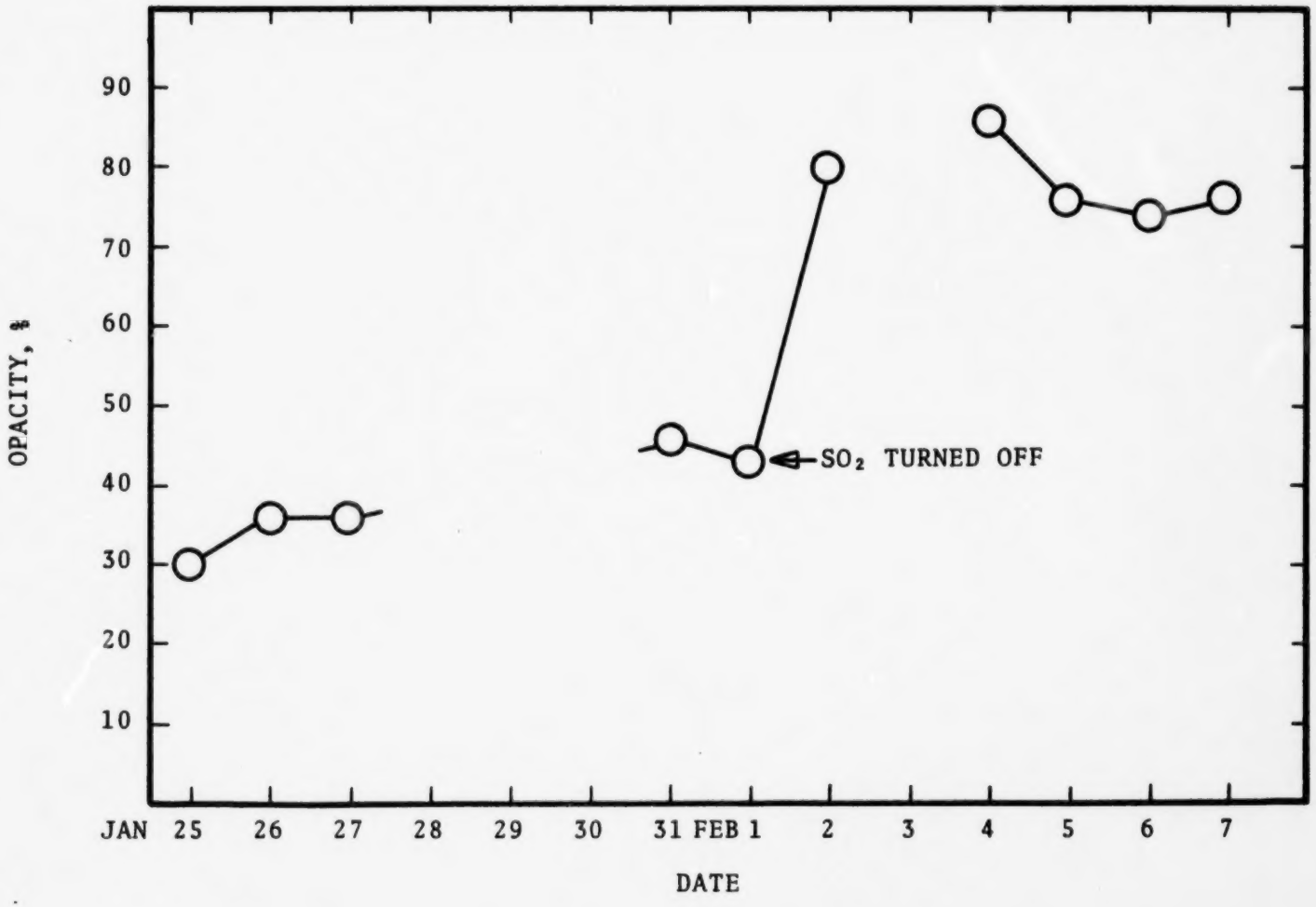

Figure 15. Opacity in outlet duct.

TABLE 8. CHEMICAL ANALYSIS OF COAL

Analyte	Sample from Conditioned Period Dry wt. %	Sample from Unconditioned Period Dry wt. %
Sodium	0.013	0.016
Potassium	0.06	0.06
Lithium	0.00019	0.00014
Calcium	0.19	0.18
Magnesium	0.02	0.02
Sulfur	1.09	0.78
Sulfur*	0.88	0.85
Ash*	10.7	11.1
Volatile hydrocarbons*	33.5	33.6
Fixed carbon*	55.8	55.7
Heat content*	30 Joules/kg (13,000 Btu/lb)	30 Joules/kg (13,100 Btu/lb)

*Averages of daily data received from the plant

SECTION 5

ECONOMICS

The ESP for unit No. 3 was put on line in 1972 at a cost of $1.4 million. It normally operates at full load capacity of 58 megawatts. The flue gas conditioning system was installed two years later. The cost of the SO_3 system was not available. The summary of the available cost data shown in Table 9 is based on dollar values as of the first half of 1977. Maintenance and operating costs for the ESP shown do not reflect the cost of power to supply the high voltage.

TABLE 9. CAPITAL AND OPERATING COSTS
UNIT NO. 3 1977 COSTS

A. Installed capital costs:

ESP, $24 per kW, Total $1,358,000; on-line 1972

Conditioning equipment: Total $ *; on-line 1974

B. Annual operation and maintenance costs (Does not include electric power or chemical cost):

ESP	$57,693
Conditioning equipment	$ 2,845

C. Chemical costs:

Conditioning agent,	unit cost	$160/ton (with freight)
		$140/ton (freight not included)
	yearly consumption	55,600 kg/year
	yearly cost	$9,814

D. Average unit costs:

ESP	0.159 mills/kW-hr
Gas conditioning	0.035 mills/kW-hr (including SO_2 cost)
	0.0078 mills/kW-hr (without SO_2 cost)

* This value not supplied by plant records

REFERENCES

Ensor, D. S., T. A. Cahill, and L. E. Sparks, "Elemental Analysis of Fly Ash from Combustion of a Low Sulfur Coal," APCA Meeting 1968, Paper No. 75-33.7, June 1975.

Gooch, J. P., J. R. McDonald, S. Oglesby, Jr., "A Mathematical Model of Electrostatic Precipitation," EPA 650/2075-037, April 1975.

Lawless, P. A., "Analysis of Cascade Impactor Data for Calculating Particle Penetration," Research Triangle Institute, EPA Contract No. 68-02-2612, Task 36, 1978.

Maddelone, R. et al., "Process Measurement Procedures: Sulfuric Acid Emissions," February 1977.

Smith, W. B. et al., "Procedures Manual for Electrostatic Precipitator Evaluation," EPA Contract No. 68-02-2131, Southern Research Institute, March 1977.

Sparks, L. E. "SR-52 Programmable Calculator Programs for Venturi Scrubbers and Electro-Static Precipitators," EPA 600/7-78-026 March 1978.

White, H. J. "Resistivity Problems in Electrostatic Precipitation," APCA, Vol. 24, No. 4, April 1974.

APPENDIX "A"

PARTICULATE SAMPLING METHODS

APPENDIX "A". PARTICULATE SAMPLING METHODS

CASCADE IMPACTOR TEST METHOD

Cascade impactor measurements were taken at the inlet and outlet of the ESP to determine the collection efficiency as a function of particle size. Calibrated UW Mk III cascade impactors were used. A schematic is shown in Figure A-1.

The particle mass entering and leaving the ESP was determined from the sum of the mass collected on all the stages (including the nozzle of the in-situ cascade impactor).

Greased Mylar and Reeve Angel glass fiber substrates were used. Substrates were baked at 205°C (400°F) for four hours and desiccated for two hours prior to weighing. To minimize weight loss and trace element contamination with greased substrates, Apiezon L grease was used. Blank test runs with twenty minutes of exposure to the actual flue gas were performed to confirm no weight gain on Reeve Angel substrates in the presence of SO_2.

The elemental composition of the fly ash was determined as a function of particle diameter. Fly ash samples were taken at the ESP outlet for this purpose daily. Particulate samples were obtained with a UW Mk III cascade impactor using 1 mil Mylar substrates, coated with Apiezon L grease. The Mylar substrates and Apiezon L grease were shown to have a low background of trace elements.

Particulate sulfate entering and leaving the ESP was obtained from the chemical analysis of the cascade impactor substrates (Reeve Angel glass fiber substrates). This was done on one inlet and one outlet run per day, as the same set of substrates could not be used for both chemical and gravimetric analysis.

The particulate sample was dissolved in CO_2-free distilled water and the amount of sulfate present was determined by a titration with NaOH with Bromophenol Blue as indicator.

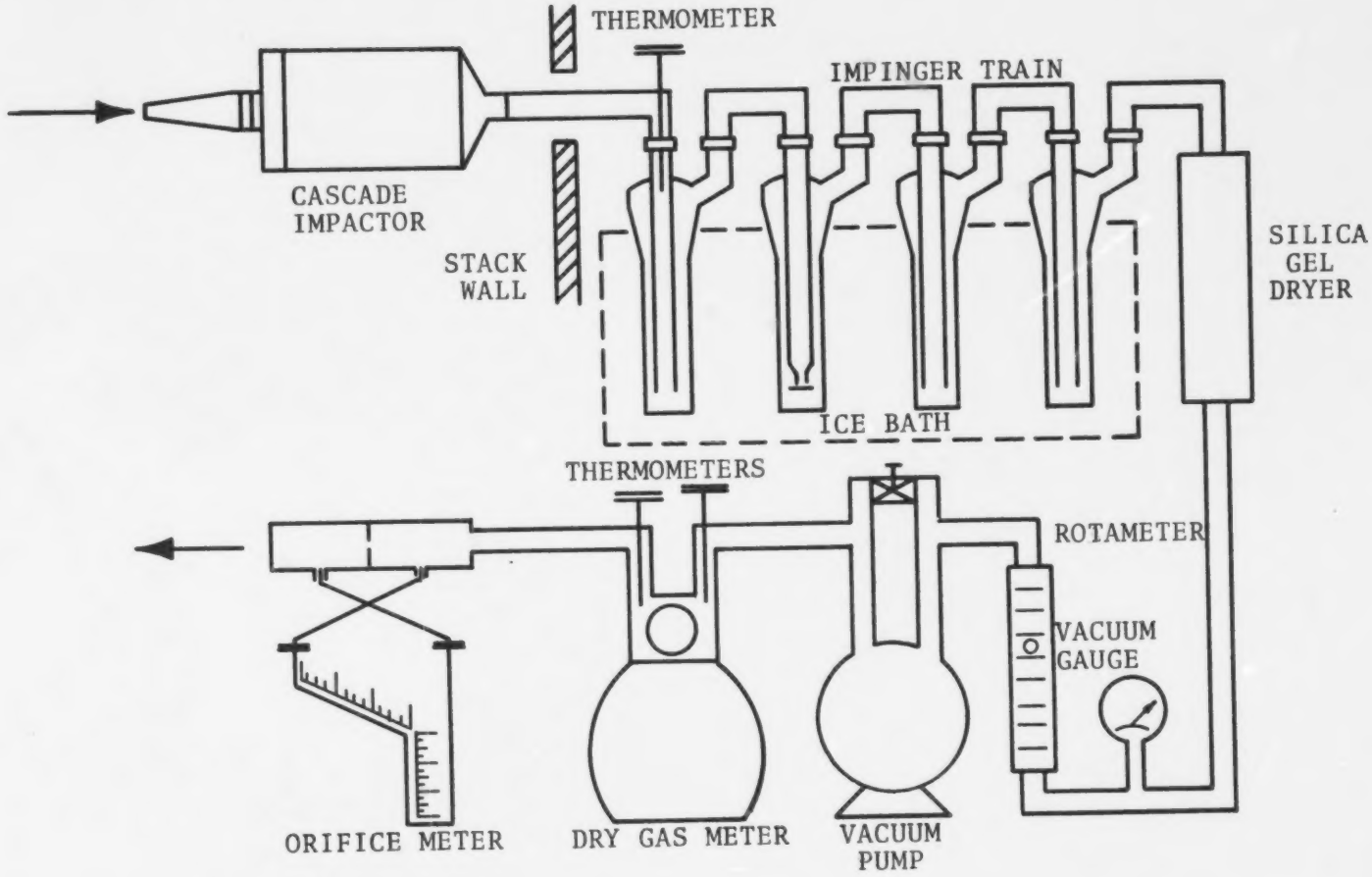

Figure A-1. Modified EPA sampling train with in-stack cascade impactor.

EPA METHOD 5 MEASUREMENTS

EPA Method 5 measurements were made to determine accurate overall mass collection efficiencies. The location of the test ports in the duct were such that a standard Method 5 would require 48 five-minute samples. The sampling time was reduced from five minutes to three minutes each to expedite the test. The molecular weight and gas density were determined with a standard Orsat analysis, according to EPA Method 3.

500 mg SAMPLE FOR BIOASSAY TESTING

Particulate samples (500 mg) were collected at the ESP outlet with one sample collected for each test condition (that is, with and without flue gas conditioning).

During the conditioned test a sample was scooped from the fly ash pile at the outlet. During the baseline tests a Method 5 train was used to collect a sample on a filter. These samples were forwarded to the EPA project officer.

APPENDIX "B"

PARTICLE SIZE DATA

TABLE B-1. INLET AND OUTLET PARTICLE DATA FOR RUN #1
Taken 1/25/78 at 11:50 am

IMPACTOR STAGE NUMBER	INLET			OUTLET		
	M_{cum} (mg/DNm^3)	d_{pc} (µmA)	d_p (µm)	M_{cum} (mg/DNm^3)	d_{pc} (µmA)	d_p (µm)
Precutter & Nozzle	2,510			105		
1	2,240	30.9	20.26	80.2	22.3	14.6
2	1,830	13.5	8.80	72.9	9.77	6.32
3	1,680	5.24	3.34	70.0	3.78	2.37
4	965	2.70	1.67	60.4	1.88	1.12
5	391	1.57	0.92	31.5	1.13	0.63
6	123	0.89	0.48	11.7	0.64	0.31
7	34.9	0.50	0.23	4.76	0.36	0.14
Filter	21.4			2.56		
Sample Volume (DNm^3)	0.0373			0.273		

TABLE B-2. INLET AND OUTLET PARTICLE DATA FOR RUN #7
Taken 1/27/78 at 2:40 pm

IMPACTOR STAGE NUMBER	INLET			OUTLET		
	M_{cum} (mg/DNm^3)	d_{pc} (µmA)	d_p (µm)	M_{cum} (mg/DNm^3)	d_{pc} (µmA)	d_p (µm)
Precutter & Nozzle	2,490	33.5	21.99	105		
1	2,120	14.7	9.57	81.1	23.6	15.4
2	1,570	5.68	3.63	71.3	10.3	6.70
3	1,370	2.93	1.82	67.4	4.00	2.52
4	655	1.71	1.02	55.2	1.99	1.20
5	328	0.96	0.52	30.4	1.20	0.68
6	197	0.55	0.26	14.8	0.68	0.34
7	59.8			6.41	0.38	0.15
Filter	22.8			3.62		
Sample Volume (DNm^3)	0.0351			0.359		

N: 20°C, 1 atm; $d_{pa} = d_p (\rho_p C')^{\frac{1}{2}}$; µmA = µm(g/cm^3)$^{\frac{1}{2}}$; ρ_p = 2.3 g/cm^3

TABLE B-3. INLET AND OUTLET PARTICLE DATA FOR RUN #12

Taken 1/31/78 at 1:40 pm

IMPACTOR STAGE NUMBER	INLET			OUTLET		
	M_{cum} (mg/DNm^3)	d_{pc} (µmA)	d_p (µm)	M_{cum} (mg/DNm^3)	d_{pc} (µmA)	d_p (µm)
Precutter & Nozzle	2,380			128		
1	2,260	31.2	20.45	102	23.5	15.38
2	1,470	13.7	8.90	83.6	10.3	6.67
3	1,050	5.29	3.37	77.7	3.99	2.51
4	486	2.72	1.68	61.3	1.92	1.15
5	185	1.58	0.93	40.3	1.18	0.67
6	70.2	0.91	0.49	27.0	0.84	0.44
7	25.1	0.47	0.21	20.9	0.37	0.14
Filter	20.1			20.1		
Sample Volume (DNm^3)	0.0399			0.556		

TABLE B-4. INLET AND OUTLET PARTICLE DATA FOR RUN #13

Taken 1/31/78 at 2:25 pm

IMPACTOR STAGE NUMBER	INLET			OUTLET		
	M_{cum} (mg/DNm^3)	d_{pc} (µmA)	d_p (µm)	M_{cum} (mg/DNm^3)	d_{pc} (µmA)	d_p (µm)
Precutter & Nozzle	2,260			145		
1	2,370	31.2	20.45	123	23.7	15.3
2	1,620	13.7	8.90	106	10.4	6.74
3	1,160	5.29	3.37	93.9	4.02	2.53
4	557	2.72	1.68	70.3	2.00	1.20
5	222	1.59	0.93	40.5	1.21	0.68
6	85.6	0.90	0.49	20.3	0.68	0.34
7	22.7	0.51	0.23	9.39	0.38	0.15
Filter	7.56			5.16		
Sample Volume (DNm^3)	0.0397			0.543		

N: 20°C, 1 atm; $d_{pa} = d_p (\rho_p C')^{\frac{1}{2}}$; µmA = µm(g/cm^3)$^{\frac{1}{2}}$; ρ_p = 2.3 g/cm^3

TABLE B-5. INLET AND OUTLET PARTICLE DATA FOR RUN #14
Taken 1/31/78 at 4:20 pm

IMPACTOR STAGE NUMBER	INLET			OUTLET		
	M_{cum} (mg/DNm^3)	d_{pc} (μmA)	d_p (μm)	M_{cum} (mg/DNm^3)	d_{pc} (μmA)	d_p (μm)
Precutter & Nozzle	2,530			136		
1	2,400	31.4	20.59	112	23.5	15.38
2	1,610	13.8	8.96	102	10.3	6.67
3	1,280	5.32	3.39	96.5	3.98	2.51
4	429	2.74	1.68	82.7	1.92	1.15
5	195	1.59	0.93	55.3	1.17	0.67
6	87.7	0.91	0.49	40.4	0.84	0.44
7	37.6	0.47	0.21	33.9	0.37	0.14
Filter	10.0			32.0		
Sample Volume (DNm^3)	0.0399			0.369		

TABLE B-6. INLET AND OUTLET PARTICLE DATA FOR RUN #16
Taken 2/1/78 at 4:10 pm

IMPACTOR STAGE NUMBER	INLET			OUTLET		
	M_{cum} (mg/DNm^3)	d_{pc} (μmA)	d_p (μm)	M_{cum} (mg/DNm^3)	d_{pc} (μmA)	d_p (μm)
Precutter & Nozzle	3,150			101		
1	2,780	33.1	21.73	79.2	22.0	14.37
2	1,910	14.5	9.45	73.7	9.63	6.23
3	1,600	5.62	3.59	72.2	3.72	2.33
4	713	2.89	1.79	50.5	1.85	1.10
5	287	1.69	1.00	24.0	1.12	0.63
6	69.6	0.95	0.52	8.78	0.63	0.31
7	13.9	0.54	0.25	2.87	0.35	0.13
Filter	8.36			1.08		
Sample Volume (DNm^3)	0.0359			0.558		

N: 20°C, 1 atm; $d_{pa} = d_p (\rho_p C')^{\frac{1}{2}}$; $\mu mA = \mu m (g/cm^3)^{\frac{1}{2}}$; $\rho_p = 2.3\ g/cm^3$

TABLE B-7. INLET AND OUTLET PARTICLE DATA FOR RUN #17
Taken 2/5/78 at 8:15 am

IMPACTOR STAGE NUMBER	INLET			OUTLET		
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	d_p (μm)	M_{cum} (mg/DNm³)	d_{pc} (μmA)	d_p (μm)
Precutter & Nozzle	2,280			588		
1	2,110	35.3	23.1	398	23.6	15.4
2	1,550	15.4	10.1	365	10.3	6.70
3	1,180	5.98	3.83	344	4.00	2.52
4	774	3.08	1.92	208	1.93	1.16
5	393	1.78	1.06	84.0	1.18	0.67
6	155	1.03	0.57	26.0	0.84	0.44
7	49.5	0.53	0.24	7.59	0.37	0.14
Filter	6.19			4.34		
Sample Volume (DNm³)	0.0323			0.369		

TABLE B-8. INLET AND OUTLET PARTICLE DATA FOR RUN #21
Taken 2/5/78 at 2:30 pm

IMPACTOR STAGE NUMBER	INLET			OUTLET		
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	d_p (μm)	M_{cum} (mg/DNm³)	d_{pc} (μmA)	d_p (μm)
Precutter & Nozzle	2,440			428		
1	2,180	32.6	21.4	290	23.7	15.98
2	1,490	14.3	9.31	253	10.4	6.72
3	1,360	5.53	3.53	214	4.01	2.53
4	675	2.85	1.77	136	1.93	1.16
5	296	1.65	0.98	67.9	1.18	0.67
6	104	0.95	0.52	25.2	0.84	0.44
7	32.0	0.49	0.22	8.85	0.37	0.14
Filter	2.67			7.87		
Sample Volume (DNm³)	0.0375			0.305		

N: 20°C, 1 atm; $d_{pa} = d_p (\rho_p C')^{\frac{1}{2}}$; $\mu mA = \mu m(g/cm^3)^{\frac{1}{2}}$; $\rho_p = 2.3\ g/cm^3$

TABLE B-9. INLET AND OU[illegible] PARTICLE DATA FOR RUN #23
Taken [illegible]5/78 at 4:45 pm

IMPACTOR STAGE NUMBER	INLET			OUTLET		
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	d_p (μm)	M_{cum} (mg/DNm³)	d_p (μmA)	d_p (μm)
Precutter & Nozzle	2,550			503		
1	2,340	33.6	22.0	365	23.6	15.41
2	1,720	14.7	9.58	348	10.3	6.69
3	1,580	5.69	3.64	336	3.99	2.51
4	811	2.93	1.82	203	1.92	1.15
5	339	1.70	1.01	117	1.18	0.67
6	144	0.98	0.54	59.0	0.84	0.44
7	16.9	0.51	0.23	32.6	0.37	0.14
Filter	2.82			27.4		
Sample Volume (DNm³)	0.0354			0.307		

TABLE B-10. INLET AND OUTLET PARTICLE DATA FOR RUN #24
Taken 2/6/78 at 1:10 pm

IMPACTOR STAGE NUMBER	INLET			OUTLET		
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	d_p (μm)	M_{cum} (mg/DNm³)	d_{pc} (μmA)	d_p (μm)
Precutter & Nozzle	2,570			514		
1	2,200	31.9	20.9	403	22.7	14.83
2	1,570	14.0	9.09	360	9.93	6.43
3	1,270	5.40	3.44	304	3.84	2.41
4	658	2.78	1.72	282	1.91	1.14
5	379	1.62	0.96	178	1.15	0.65
6	196	0.92	0.50	128	0.65	0.32
7	32.2	0.52	0.24	109	0.36	0.14
Filter	7.43			104		
Sample Volume (DNm³)	0.0404			0.334		

N: 20°C, 1 atm; $d_{pa} = d_p (\rho_p C')^{\frac{1}{2}}$; μmA = μm$(g/cm^3)^{\frac{1}{2}}$; $\rho_p = 2.3\ g/cm^3$

TABLE B-11. INLET AND OUTLET PARTICLE DATA FOR RUN #26

Taken 2/6/78 at 4:00 pm

IMPACTOR STAGE NUMBER	INLET			OUTLET		
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	d_p (μm)	M_{cum} (mg/DNm³)	d_{pc} (μmA)	d_p (μm)
Precutter & Nozzle	2,470			427		
1	2,270	32.4	21.3	356	23.2	15.21
2	1,600	14.2	9.25	272	10.2	6.59
3	1,400	5.50	3.51	259	3.94	2.48
4	597	2.83	1.75	141	1.96	1.18
5	173	1.65	0.98	91.5	1.18	0.67
6	51.7	0.93	0.51	34.5	0.66	0.33
7	18.1	0.53	0.24	11.7	0.38	0.15
Filter	7.75			7.91		
Sample Volume (DNm³)	0.0387			0.316		

TABLE B-12. INLET AND OUTLET PARTICLE DATA FOR RUN #28

Taken 2/6/78 at 6:10 pm

IMPACTOR STAGE NUMBER	INLET			OUTLET		
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	d_p (μm)	M_{cum} (mg/DNm³)	d_{pc} (μmA)	d_p (μm)
Precutter & Nozzle	2,150			510		
1	1,940	32.3	21.2	354	22.7	14.82
2	1,330	14.1	9.21	312	10.4	6.72
3	926	5.47	3.49	301	4.01	2.53
4	483	2.82	1.75	174	2.00	1.20
5	212	1.64	0.97	87.9	1.20	0.68
6	66.5	0.93	0.51	33.4	0.68	0.34
7	15.3	0.53	0.24	10.8	0.38	0.15
Filter	12.8			8.20		
Sample Volume (DNm³)	0.0391			0.305		

N: 20°C, 1 atm; $d_{pa} = d_p (\rho_p C')^{\frac{1}{2}}$; $\mu mA = \mu m (g/cm^3)^{\frac{1}{2}}$; $\rho_p = 2.3$ g/cm³

TABLE B-13. INLET AND OUTLET PARTICLE DATA FOR BLANK RUN #3
Taken 1/25/78 at 3:45 pm

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	Loading mg	d_{pc} (μmA)	Loading mg	d_{pc} (μmA)
Probe	17.6		7.7	
Pre-filter	151.0		41.0	
1	-0.1	26.8	0.0	21.3
2	-0.3	11.8	-0.1	9.3
3	-0.4	4.45	-0.3	3.49
4	-0.3	2.28	-0.1	1.82
5	-0.3	1.29	-0.3	1.02
6	-0.6	0.72	-0.2	0.57
7	-0.3	0.42	-0.3	0.33
Filter	-0.4		0.0	
Sample Volume (DNm^3)	0.051		0.349	

TABLE B-14. INLET AND OUTLET PARTICLE DATA FOR BLANK RUN #5
Taken 1/27/78 at 9:10 am

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	Loading mg	d_{pc} (μmA)	Loading mg	d_{pc} (μmA)
Probe	8.9		13.0	
Pre-filter	105.6		29.6	
1	0.0	28.9	0.0	20.6
2	-2.0	12.7	-0.2	9.1
3	-0.1	4.80	-0.2	3.4
4	-0.1	2.47	0.0	1.8
5	0.0	1.39	0.0	0.99
6	-0.2	0.78	-0.1	0.55
7	0.0	0.45	0.0	0.32
Filter	0.0		35.9	
Sample Volume (DNm^3)	0.044		0.410	

N: 20°C, 1 atm; $d_{pa} = d_p (\rho_p C')^{\frac{1}{2}}$; $\mu mA = \mu m(g/cm^3)^{\frac{1}{2}}$; $\rho_p = 2.3\ g/cm^3$

TABLE B-15. INLET AND OUTLET PARTICLE DATA FOR BLANK RUN #10
Taken 1/31/78 at 8:25 am

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	Loading mg	d_{pc} (μmA)	Loading mg	d_{pc} (μmA)
Probe	5.2		13.8	
Pre-filter	160.1		58.5	
1	0.1	28.3	0.0	20.4
2	-0.1	12.4	-0.1	8.92
3	-0.2	4.69	0.0	3.34
4	-0.2	2.41	0.0	1.73
5	-0.2	1.36	-0.1	0.98
6	-0.1	0.76	-0.1	0.55
7	-0.3	0.44	-0.2	0.32
Filter	0.0		10.4	
Sample Volume (DNm^3)	0.047		0.583	

TABLE B-16. INLET AND OUTLET PARTICLE DATA FOR BLANK RUN #19
Taken 2/5/78 at 10:30 am

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	Loading mg	d_{pc} (μmA)	Loading mg	d_{pc} (μmA)
Probe	14.2		36.1	
Pre-filter	122.2		87.5	
1	0.3	26.6	0.1	20.6
2	0.0	11.7	0.3	9.1
3	0.0	4.42	0.3	3.4
4	-0.1	2.28	0.3	1.8
5	0.0	1.29	0.1	1.0
6	0.0	0.72	0.1	0.55
7	0.0	0.42	0.0	0.32
Filter	0.1		6.3	
Sample Volume (DNm^3)	0.042		0.168	

N: 20°C, 1 atm; $d_{pa} = d_p (\rho_p C')^{\frac{1}{2}}$; $\mu mA = \mu m (g/cm^3)^{\frac{1}{2}}$; $\rho_p = 2.3\ g/cm^3$

APPENDIX "C"

PARTICULATE SULFATE DATA

TABLE C-1. RESULTS OF PARTICULATE SULFATE TESTS, mg/DNm³ OF GAS SAMPLED

	Conditioned Tests				Baseline Tests							
Run No.	2		8		11		18		22		29	
Stage	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
1	2.10	1.49	1.14	0.13	*	1.09	1.08	0.09	*	*	*	*
2	1.05	0.21	0.33	0.08	*	0.23	*	*	*	*	*	*
3	0.90	0.17	1.14	0.14	*	*	*	*	*	*	*	*
4	0.30	0.23	0.49	0.18	*	*	*	*	*	*	*	*
5	0.30	0.27	0.33	0.14	*	*	*	*	*	*	*	*
6	0.30	0.19	0.65	0.16	2.60	*	*	*	*	*	*	*
7	0.30	0.19	0.65	0.13	*	*	*	*	*	*	*	*
Filter	0.30	0.15	0.49	0.14	*	*	*	0.33	*	6.72	*	0.28

* Below detectable limit

APPENDIX "D"

INPUT DATA FOR THE ESP PERFORMANCE MODEL

TABLE D-1. INPUT DATA FOR THE ESP PERFORMANCE MODEL PROGRAM*

Case	d_{pg}	σ_g	a	b	c	A_p/Q_G	σ	N_s	S	di	d_f	Δd
Baseline 0.1-2 μm	8.5	4.0	1.16	0.300	0.212	0.36	0.25	2	0.1	0.1	2.0	0.1
Baseline 2-20 μm	8.5	4.0	0.948	0.817	-3.50×10^{-4}	0.36	0.25	2	0.1	2	20	1
SO_3 Conditioning 0.1-2 μm	8.5	4.0	2.85	1.06	0.486	0.36	0.25	2	0.1	0.1	2	0.1
SO_3 Conditioning 2-20 μm	8.5	4.0	2.25	2.33	0.00265	0.36	0.25	2	0.1	2	20	1

Enter Data

Mass mean particle diameter, d_{pg} (μm)

Geometric standard deviation, σ_g

First curve fit parameter for migration velocity, a

Second curve fit parameter for migration velocity, b

Third curve fit parameter for migration velocity, c

Specific collector area, A_p/Q_G ($cm^2/Acm^3/sec$)

Normalized standard deviation of gas velocity distribution, σ

Number of baffled sections, N_s

Sneakage-reentrainment fraction, S

Initial particle diameter, d_i (μm)

Final particle diameter, d_f (μm)

Particle diameter increment, Δd (μm)

* Sparks (1978)

APPENDIX "E"

ELEMENTAL ANALYSIS DATA

APPENDIX "E". ELEMENTAL ANALYSIS DATA

Thirty elements were included in the UC Davis X-ray Analysis of the cascade impactor substrates. Of these thirty only eight were present in significant amounts. Table E-1 lists the thirty elements and representative minimum resistivities.

Table E-2 presents the weight per substrate area, by cascade impactor stage, for the eight elements which were present in large enough amounts to be of interest.

TABLE E-1. MINIMUM SENSITIVITIES OF ELEMENTS, ng/cm^2

Na	2,158	V	172	Hg	725
Mg	615	Cr	149	Pb	864
Al	653	Mn	150	Sn	374
Si	613	Fe	157	Ag	1,856
S	470	Co	151	Br	459
Cl	443	Ni	116	Rb	740
K	279	Cu	89	Sr	1,013
Ca	198	Zn	107	Zr	1,502
Ba	550	Pt	566	Mo	2,351
Ti	168	Au	652	Pd	4,660

TABLE E-2. RESULTS OF ELEMENTAL ANALYSIS OF FLY ASH ON CASCADE IMPACTOR SUBSTRATES

Run / Stage	ng/cm²							
	Al	Si	S	K	Ca	Ti	Fe	Zn
16*								
1	2430	5147	5665	1434	3513	1940	22088	244
2	2657	6870	8467	1201	4365	1312	20449	277
3	8322	15504	2543	4276	4507	5180	33215	266
4	2836	5222	4739	1273	3926	1606	10695	166
5	2920	5351	5904	1562	2560	2212	15078	257
6	206	855	4116	510	1508	784	5436	155
7	***	***	4399	148	1562	604	2100	165
34**								
1	60832	101540	***	21842	16813	29718	201947	1480
2	21055	37357	1427	6452	12073	7032	34750	348
3	25877	40427	261	9008	7398	10654	62852	464
4	25513	41872	467	8380	7562	8568	49857	388
5	4621	8201	350	1796	3886	2102	12375	154
6	4628	8921	506	1686	4415	2046	13017	472
7	1750	3483	286	743	3817	1056	5520	106
24**								
1	***	1509	1133	5550	7763	8802	56112	598
2	11464	21887	3113	2923	6252	3384	17258	236
3	32192	52636	679	10957	9717	12378	82818	420
4	37295	60104	***	13488	10504	14556	99906	597
5	10990	20011	397	3988	6607	4372	27685	316
6	3922	7084	565	1530	5410	1998	11698	183
7	1539	2953	400	655	1713	519	5211	141

* Conditioned test

** Baseline test

*** Below significant limit